Studies on the Mechanism of Deformation of Sedimentary Rocks in the Iwaki Area of the Joban Coal-Field, Fukushima Prefecture

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Shinobu Mitsui

ABSTRACT

The results of stratigraphic studies and structural analysis of the major faults, minor faults and joints, determination of the principal stress based on the analysis of minor faults, and the relationship between faults and joints, besides other geological features of the Iwaki Area in the Joban coal-field, Fukushima Prefecture are presented. The origin of the faults and joints were interpreted from the results obtained from experiments on the deformation by the tri-axial compression test.

The area studied was classified into the three provinces of Futaba, Iwaki North and Iwaki South Areas, each being separated by the Yunotake and Futatsuya faults of pre-Iwaki age the lowest of the Tertiary stratigraphic units. Provenance influence on the respective sedimentary basins was reflected in the rock units from the Iwaki up to and including the Takaku. The Takaku Group is superposed by the Izumi Group with unconformity. Most of the faults cutting the Tertiary sedimentary rocks were developed by the strong influence of the basement faults of WNW-ESE trend. The joints in the investigated area were formed by the structural control of the basement rocks. From the field evidence and tri-axial compression experiments, it became clear that most of the faults and joints that cut the Tertiary rocks in the area surveyed, were formed by reflection the vertical movements before the deposition of the Izumi Group and by the structural control of the basement rocks, after development of the fold structures, and that those structures were developed at a not very deep position below the surface.

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INTRODUCTION AND ACKNOWLEDGMENTS

The geology of the Joban Coal-field, distributed in southeast Fukushima and northeast Ibaraki Prefectures, had been investigated by many authors since Nakamura (1913), particularly because of the economic importance and in being a classical locality for the stratigraphy of the Pacific Coast of central and eastern Honshu, Japan. Hanzawa (1957), and Sugai and Matsui (1957) from the stratigraphical standpoints and Kamada (1962) from molluscan biostratigraphy contributed to the geology of the Joban Coal-field. But, many problems still remained, and among them that of the so-called "Taga group", still remains regardless of the various opinions expressed to date. Only Hoshino (1965) and Tsuneishi (1966) contributed to the geologic structure of this area.

The purpose of the present paper is to describe and interpret the geological structure of the Iwaki area of the Joban Coal-field. Emphasis was given to the geologic structure and stratigraphical classification of the Tertiary rocks, measurements and analysis of the major faults, minor faults and joints, determination of the principal stress based on the analysis of minor faults, and the relationship between fault and joint, besides other geological features. The faults were interpreted in connection with the results obtained from experiments on the deformative actions by the tri-axial compression test.

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STRATIGRAPHY

The area investigated includes Iwaki City and Hirono-cho and Naraha-cho, Futaba-Gun, Fukushima Prefecture (Fig. 1), and covers, in the scale of 1:50,000, the topographical maps of Ide, Kawamae, Taira, Onahama, Takenuki and Ogawa.

I. BASEMENT ROCKS

The basement rocks of the Tertiary sediments in the surveyed area are the Abukuma metamorphic rocks, the Paleozoic rocks, pre-Tertiary granitic rocks and the

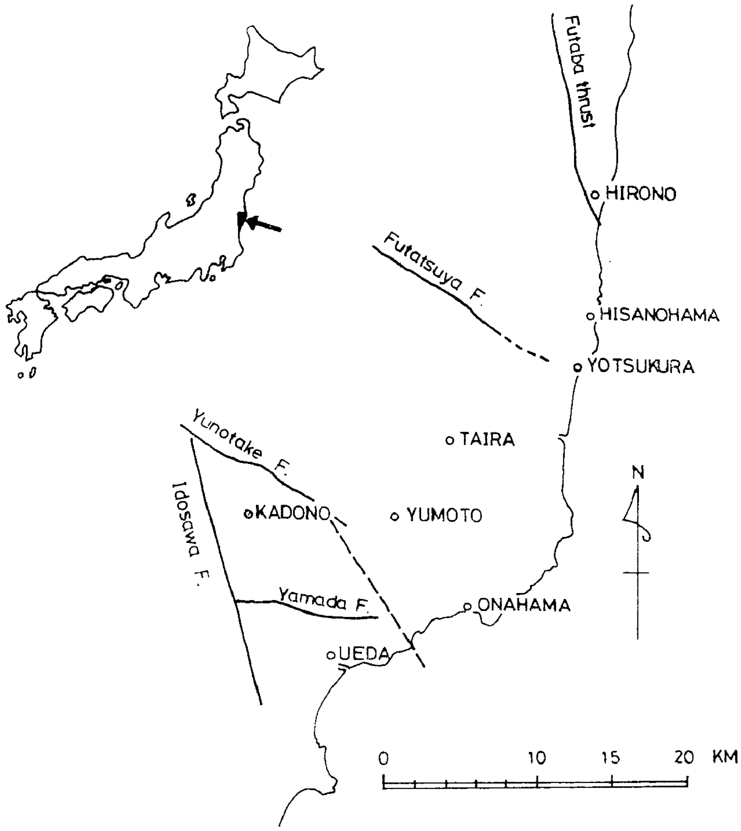


Fig. 1. Index map of the investigated area

Cretaceous sediments. Ultrabasic and basic igneous rocks that intruded before and after the pre-Tertiary granitic rocks are also exposed.

Abukuma Metamorphic Rocks: – The rocks consist of actinolite schist, amphibolite-mica schist, green crystalline schist and amphibolite schist, etc. Besides, lavas of basic igneous rocks, tuff and crystalline limestone have been reported (Iwao and Matsui, 1961). The strike is N-S with dips of 60–90 degrees to the east or west.

The Abukuma metamorphic rocks were formed by one cyclic regional metamorphism during the Early Cretaceous age according to Miyashiro (1965), and to poly-metamorphism according to the Research Group of the Abukuma Plateau (1969).

Paleozoic Rocks: – The rocks are Permian in age and distributed on the northern and eastern sides of Mt. Takakura-yama and called the Takakurayama Group (Yanagisawa, 1967). The group consists of black slate, sandstone, conglomerate and phyllite, etc., with intercalated small fossiliferous limestone lenses. The fold axis and schistosity strike N-S but change to NE-SW near the Futatsuya fault.

Granitic Rocks: – Granitic rocks are widely distributed in the surveyed area. In the Futaba Area granitic rocks are superposed with unconformity by the Cretaceous Futaba Group and Iwaki Formation, the lowest of the Tertiary stratigraphic units. The granitic rocks intrude the Abukuma metamorphic rocks near the Yunotake fault and the western parts of the Idosawa fault. The rocks are hornblende-biotite granodiorite, and the age of intrusion is pre-Futaba; the age is dated to be 95×10^6 years by the Potassium-Argon method (Kawano and Ueda, 1965).

Basic and Ultrabasic Rocks: – Quartz diorite, gabbro, pyroxenite, serpentine and peridotite, etc. are distributed in the north of the Futatsuya fault, the vicinity of Mt.

Mizuishi-yama, north of the Yunotake fault and the environs of Hiraishi, Tabito-cho. These rocks intrude the Abukuma metamorphic rocks and also rarely along the Nekonaki and Yaguki faults.

Cretaceous Sediments: – The Cretaceous Futaba Group (Fig. 2), crops out only in the Futaba Area (north of the Futatsuya fault). This Group overlies the Abukuma metamorphic rocks, the granitic rocks and the Paleozoic rocks with unconformity, and is superposed by the Tertiary with unconformity. The group has N-S strike in the northern area but it changes to NNE-SSW towards the southern area; the dip is about 10°E. The units of the group offlap in succession towards the north and is overlain with unconformity by the Tertiary System of N-S to NNW-SSE in general strike. The Tamayama Formation, dies out in the vicinity of Komatsu, the next or middle unit, the Kasamatsu Formation is distributed to the north of Komatsu, Hirono-cho, and the lowest or Ashizawa Formation to the north of Osaka, Naraha-cho.

The Futaba Group occurs as a subsurface unit in the south of the Futatsuya fault.

The Early Cenomanian consists generally of massive, fine grained sandstone attaining about 100 to 200 meters in thickness.

The Kasamatsu Formation, about 140 meters in thickness, consists mainly of coarse grained arkose sandstone showing cross-lamination and is intercalated with layers of mudstone and lignite.

The Tamayama Formation, 60 to 120 meters in thickness, is composed mainly of coarse grained arkose sandstone with conglomerates and cross lamination in part and with intercalated lignite layers in the upper part.

The geological age of the Futaba Group, according to Obata (1967), Obata and Suzuki (1969) from the molluscan fossils and Takayama and Obata (1968) from the Nannoplankton fossils ranges from the lower Urakawa Series (Coniacian) to the lower part of the Upper Urakawa Series (Santonian).

II. TERTIARY AND QUATERNARY SEDIMENTARY ROCKS

In the area surveyed the Tertiary sedimentary rocks are classified, from the older to the younger, into the Shiramizu Group, Yunagaya Group, Nakayama Formation, Takaku Group, Izumi Group and Yamadahama Formation. Each group and formation are characterized by the development of cyclic sedimentation. On the other hand, the Quaternary sedimentary rocks includes only the Sodetamayama Formation and the terrace deposits (Fig. 2). The geological map of the area is shown in Fig. 3.

SHIRAMIZU GROUP (Nakamura, 1913), (Fig. 4)

This Group is subdivided into the Iwaki Formation, the Asagai Formation and the Shirasaka Formation in upward succession and represents a transgressive facies.

1. IWAKI FORMATION (Tokunaga, 1927). (Fig. 5)

Type locality: The vicinity of Hiwatari, Joban-Yumoto-machi, Iwaki City, Fukushima Prefecture. Thickness: 100 to 430 meters.

Lithology: In the area between the Futatsuya and the Yunotake faults this formation, 350 to 430 meters in thickness, overlies granitic rocks with basal conglomerate. It makes a homoclinal structure with general strikes of N10°W to N10°E and dips of about 10°E.

In this area the formation is subdivided into, in upward succession, 1) lower part of conglomerate, sandstone and mudstone intercalated with beds of the main coal, 2) middle part mainly of conglomerate and sandstone, 150–200 meters in thickness and, 3) the upper part mainly of sandstone. The three parts grade into one another.

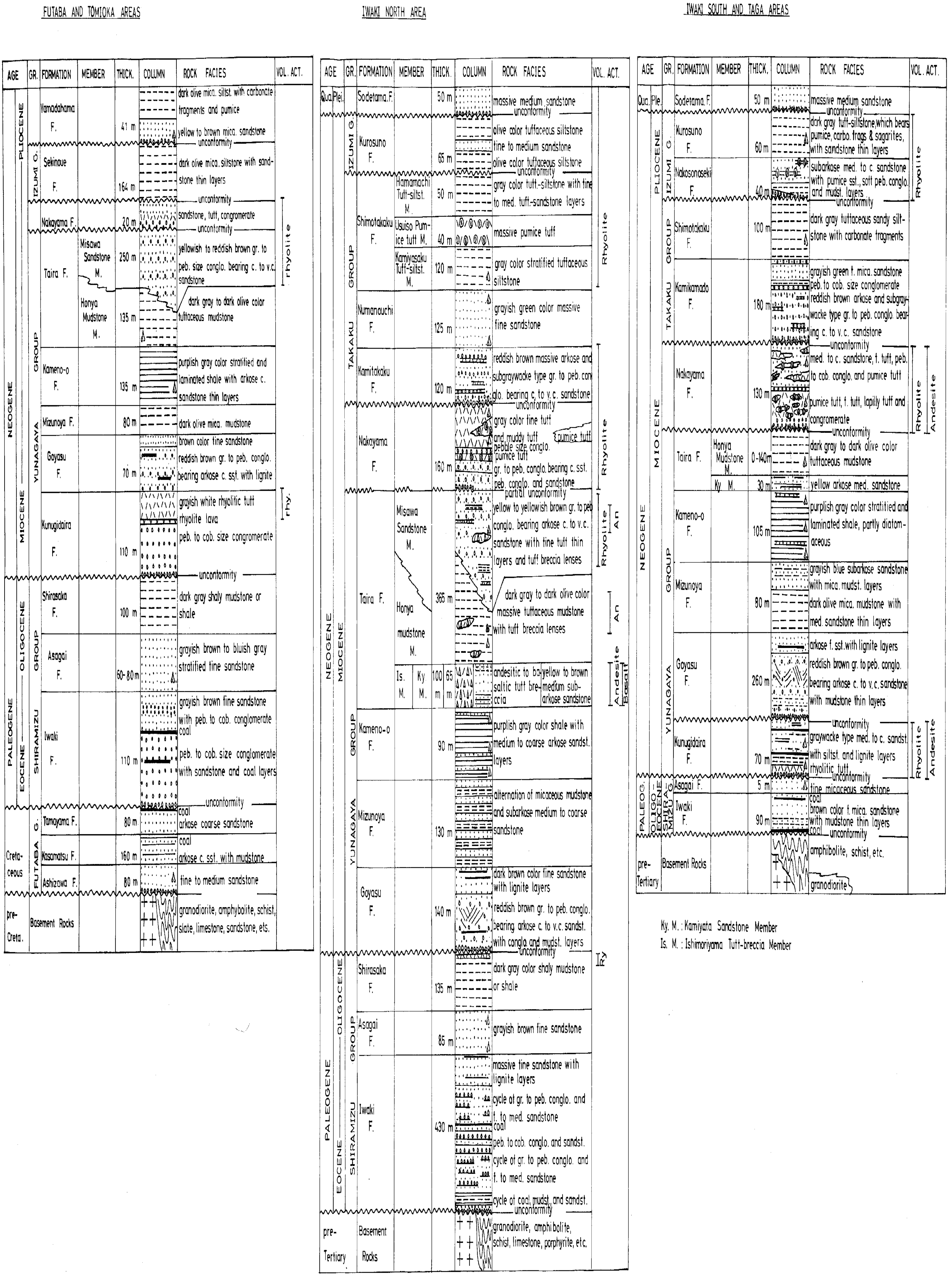


Fig. 2. Composite columnar section

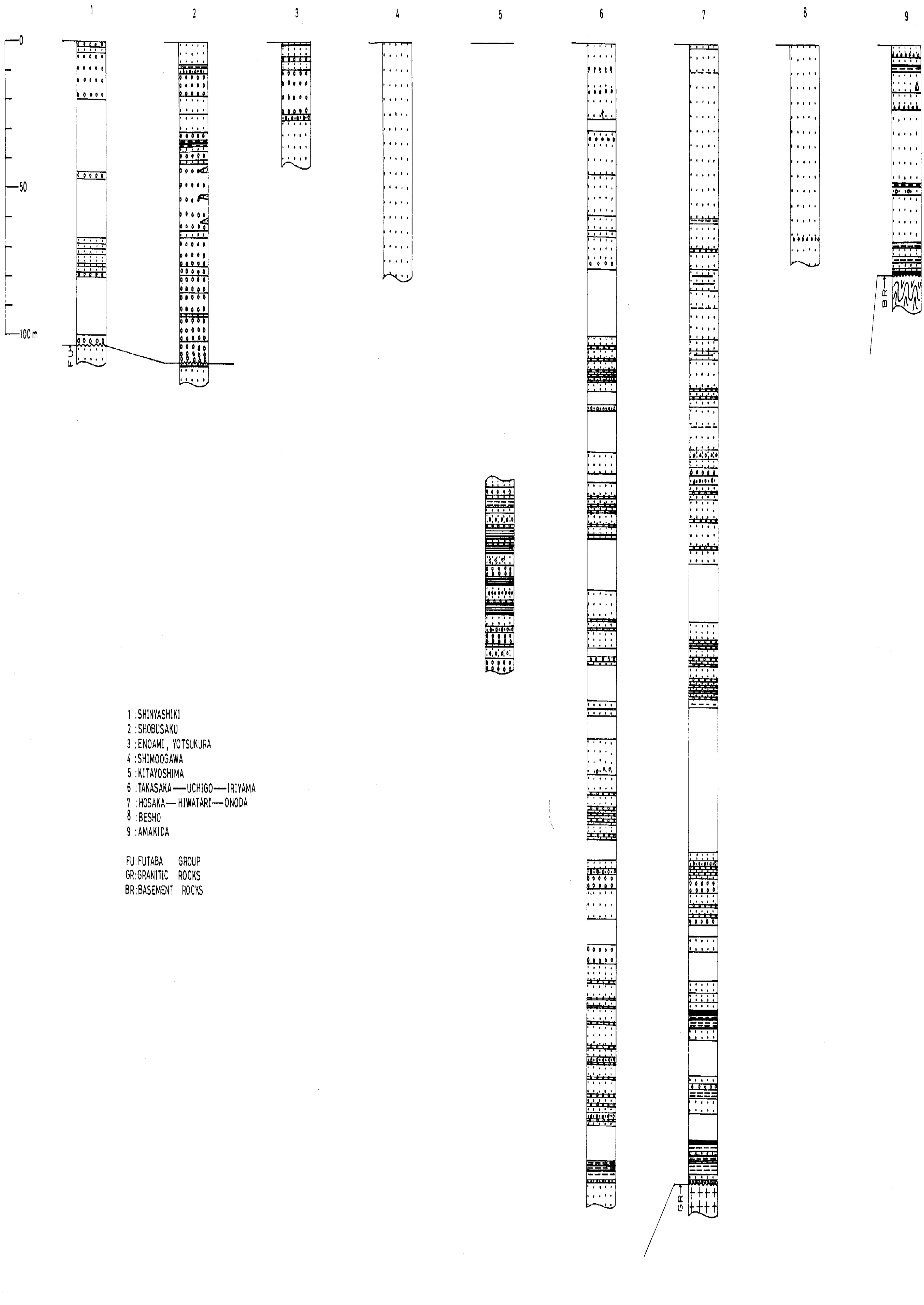


Fig. 5. Columnar sections of the Iwaki Formation

The lower part, 80 to 100 meters in thickness consists of conglomerate, sandstone and mudstone, each of about the same thickness and shows cyclic sedimentation. The conglomerates are subangular, pebble to cobble size, and composed mainly of chert, slate and sandstone. The sandstone is fine to coarse grained and with conglomerate in part. The main coal beds average about 0.2 to 0.6 meters in thickness.

The middle part, 150 to 200 meters in thickness, is composed mainly of conglomerate and sandstone, the former is dominant in the lower and the latter in the upper. The conglomerates of cobble to pebble size are dominant in the lower part and those of pebble to granule size are dominant in the upper. The conglomerate is mainly of chert, slate and sandstone. Especially, a few cobble size conglomerate beds, 5 to 10 meters in thickness, are developed in the vicinities of Iriyama, Miya and Inohana. When observed in detail, cyclic sedimentation of conglomerate-sandstone-mudstone-coal or lignite can be observed in this middle part; the mudstone and coal of this part are thinner than that of the lower part.

The upper part, 50 to 200 meters in thickness, is distributed in the vicinities of Ogawa, Ogawa-cho and Hiwatari, Joban-Yumoto-machi and consists mainly of fine to medium grained sandstone intercalated with thin layers of mudstone, conglomerate, and lignite or coal. The conglomerate is almost of pebble to cobble size and mainly of chert, slate and sandstone. The sandstone is generally massive, fine to medium grained, micaceous and shows cyclic sedimentation.

In the Taga area south of the Yamada fault, this formation represents the lower to middle part and is 80–100 meters thick. It is composed mainly of fine grained sandstone intercalated with layers of conglomerate, coarse grained sandstone and mudstone and overlies the metamorphic rocks with angular unconformity. The formation is homoclinal with N10° to 30°W strike and 10°E dip. Cross lamination, pull-apart structures, *Ostrea* bed and sand-pipes occur in the sandstone.

In the Futaba Area this formation, about 100 meters in thickness, makes a homoclinal structure with general strikes of N-S to NNW-SSE with dips of 10° to 20°E. It lies on the Cretaceous Futaba Group with unconformity. The conglomerate is composed mainly of pebbles to cobbles of subangular to subrounded chert, slate, sandstone, quartz-porphyry and granitic rocks intercalated with layers of coarse grained conglomerate bearing sandstone, fine to coarse grained sandstone, mudstone and coal. It shows cyclic sedimentation in part (Eguchi *et al.*, 1954). The sandstones are micaceous fine to coarse grained, with dominant cross laminations and merges into the conglomerate. Thus, it is difficult to separate the Shiramizu Sandstone from the Iwaki Sandstone.

In the vicinities of Tanabe and Izumida the Iwaki Formation is concealed in the subsurface. Here the upper part consists of fine to coarse grained sandstone and the lower of conglomerate and conglomerate bearing sandstone.

Sedimentary environment: In the Iwaki North Area or the north-central part of the field the lower part of the Iwaki Formation is composed of conglomerate, sandstone and mudstone of about the same thickness and is intercalated with the main coal beds. This facies is almost terrestrial in the origin, except for a part which is of marine facies. In detail cyclic sedimentation, comprising mainly sandstone, mudstone and coal with thin conglomerate beds is developed in the southern part of the field. The conglomerate beds become thicker towards the north, and the lower part of the formation shows cyclic sedimentation of mainly conglomerate in the vicinity of Ogawa-cho.

From the above, during the lower stage of this formation in the southern part of the field the environment was one where sandstone and mudstone were deposited dominantly. This shows that the physical conditions differed with area.

The upper part of the formation consists mainly of fine grained sandstone. This lithofacies suggests that the Iwaki Formation had gradually changed into a neritic environment in the environs of Nanamagari.

From the lithology and field evidence it is inferred that the Iwaki Formation in this area gradually changed from partially terrestrial to a transgressive facies during which time there was repeated rhythmic subsidence, and that the enviromental conditions were varied as stated above.

From the variations in the thickness and rock facies, during sedimentation of the Iwaki Formation, it is inferred that the Futaba Area was small in the grade of depression and alluvial sediments were deposited near the seashore, whereas in the Iwaki North Area, the Iwaki South Area and the Taga area the rate of depression exceeded that of the Futaba Area and abundant sand and mud were deposited under a littoral to neritic environment.

The Cretaceous Futaba Group in the Futaba Area is superposed by the Iwaki Formation with unconformity and is exposed at the surface, whereas in the Iwaki North Area it is concealed underground and lies directly on the basement rocks with unconformity.

From the above descriptions, different sedimentary environments and different tectonic movements are recognized at the time of sedimentation of the Futaba Group and before deposition of the Iwaki Formation. Thus, the three sedimentary divisions of the Futaba Area, the Iwaki North Area and the Iwaki South Area were formed in relation to the Futatsuya and Yunotake faults which make the boundaries of the respective tectonic units.

Geological age: The geological age of the Iwaki Formation is Upper Eocene from the occurrence of *Anthracotherium* (Takai, 1961).

2. ASAGAI FORMATION (Tokunaga, 1927)

Type locality: Kasamatsu pond east of Hosaka, Joban-Yumoto-machi, Iwaki City, Fukushima Prefecture. Thickness: 80 to 130 meters.

Lithology and stratigraphic relationship: The formation consists almost of fine to medium grained sandstone intercalating marly concretions; it becomes fine grained towards the upper part. Molluscan fossils are preserved in the sandstone and marly concretions. In the northern part of the field it lies on the Iwaki Formation with conformity, the general strike is N-S, and dips of about 10°E. It makes a homoclinal structure with the Iwaki Formation. The thickness of the formation is 130 meters in the vicinity of Uenohara, 50 meters in the environs of Hosaka and 20 meters at Bessho.

In the Taga area the Asagai Formation, 5 meters in thickness and of fine sandstone, is distributed only in the environs of Inoue.

In the Futaba Area the Asagai shows strikes of N-S to NNW-SSE and dips of 10° to 30°E. The thickness is 20 to 80 meters. It consists mainly of fine grained sandstone, but with discontinuous conglomerate beds near the boundary with the Iwaki Formation in the vicinity of Shinyashiki, Hirono-cho and the south side of the Kido River. The conglomerate is mainly of chert, sandstone, shale and quartz porphyry.

Sedimentary environment: Asano (1949), Hatai and Kamada (1950) and Kamada (1962), stated that the formation was deposited in the neritic zone under the influence of cold water. Thus, it is considered that the typical transgression of the Shiramizu Group began with the beginning of the formation.

Geological age: The Asagai Formation yielded molluscan fossils as *Acila* (*Truncacila*) *oyamadaensis* Kamada, *Venericardia* (*Cyclocardia*) *tokunagai* Yokoyama, *Turritella* cf. *tokunagai* Yokoyama and *Yoldia* (*Yoldia*) *asagaiense* Makiyama, etc., all which are characteristic of the Oligocene. The Oligocene age of the Formation is also upheld by the benthonic foraminifers (Asano and Takayanagi, 1965).

3. SHIRASAKA FORMATION (Tokunaga, 1927)

Type locality: Shirasaka, Joban-Yumoto-machi, Iwaki City, Fukushima Prefecture. Thickness: 30 to 150 meters.

Lithology and stratigraphic relationship: In the Iwaki North Area this formation has the same distribution as the Asagai with which it is conformable. It makes a homoclinal structure with N-S general strike and dips of 10°E. The thickness is 150 meters at Joban-Fujitana and 30 meters at Joban-Bessho, averaging about 100 meters. The Shirasaka is composed of massive tuffaceous shaly mudstone in which fossils are very rare. It shows good development of joints. At Uchigo-Numajiri and Shichiku coal-balls are intercalated in the upper part of the formation. In the Iwaki North Area it is superposed by the Goyasu Formation with unconformity.

In the Iwaki South Area the formation is not exposed at the surface, but lies concealed in the vicinity of Tanabe, Izumi-cho, as shown by the boring data (Exploitation for natural gas of the Joban district, 1962).

In the Futaba Area the Shirasaka makes a homoclinal structure with and N-S to NNW-SSE strikes and 15° to 45°E dips. Along the Futaba thrust fault, the dips become 30° to 45°E and the formation is more flexured than the Asagai Formation. The Shirasaka of about 100 meters in thickness is composed of massive shaly mudstone showing good development of joints. In the present area the formation is superposed with unconformity by the Kunugidaira Formation, the lowest unit of the Yunagaya Group.

Sedimentary environment and geological age: Because molluscan fossils similar to the Asagai Formation occurred from the Shirasaka at Shimo-Kitahazama, Hirono-cho and in the galley of Usuda, Isohara-cho, the age may be Oligocene (Eguchi *et al.*, 1954). The lithological characters are more fine grained than the Asagai Formation, thus it is considered that the transgression of the Shiramizu Group, which began during deposition of the Asagai Formation attained its maximum during Shirasaka time.

YUNAGAYA GROUP (Nakamura, 1913), (Fig. 6)

The Yunagaya Group lies on the Shiramizu with unconformity and is superposed by the Nakayama Formation with unconformity (partial conformity). The Group is also superposed directly by the Izumi Group with unconformity. Like the Shiramizu Group, this Group has layers of coal and lignite in the lower part, and volcanic sediments in the early and later stages. It is of interest that the regressive phase represented by the Misawa Sandstone Member was preserved from subsequent erosion.

This Group is subdivided into the Kunugidaira, Goyasu, Mizunoya, Kameno-o and the Taira formations. The latter is subdivided into the Kamiyata Sandstone, the Ishimoriyama Tuff-breccia, the Honya Mudstone and the Misawa Sandstone members. The group shows cyclic sedimentation of large scale.

The thickness of this Group ranges from 300 to 500 meters in the Futaba Area, 500 to 600 meters in the Iwaki North Area and about 400 meters in the Iwaki South Area.

The Goyasu Formation, which seems to have been deposited in the litoral zone, is thick in the vicinities of Ogawa and Kadono which are marginal areas of the sedimentary basins. The Kameno-o Formation, which represents the maximum phase in transgression is thick whereas the Goyasu Formation is thin in the environs of Yumoto, Ebata and Izumida. This points to that the Yunagaya sea invaded from the southeast.

The remarkable change in lithology and sedimentary condition is recognized in the Yunagaya Group; in the Futaba Area, the Mizunoya and Kameno-o formations and the Honya Mudstone Member consist almost of muddy rocks; whereas in the Iwaki North Area, they are of a large scale alternation of muddy rocks, and include the lower part of the Mizunoya, the Kameno-o, and the Honya Mudstone Member, these strata are overlain by the Kamiyata and Misawa Sandstone members. The shale of the Kameno-o Formation is stratified and laminated in the Futaba and Iwaki South Areas, but not in the Iwaki North Area. In the Futaba Area the Kunugidaira Formation overlies the Shiramizu Group with unconformity; whereas, the Goyasu Formation without the Kunugidaira overlies the Shiramizu in the Iwaki North and Iwaki South Areas with unconformity.

These facts point to that the present field was divided into three sedimentation areas of the Futaba, Iwaki North and Iwaki South during deposition of the Group and each area represented a structural unit, being separated from one another by the Futatsuya and Yunotake faults.

The Group in Miocene in age from the molluscan and foraminiferan fossils.

1. KUNUGIDAIRA FORMATION (Hanzawa, 1954)

The Iwaki coal-bearing Formation (Watanabe, 1934) and the Taki coal-bearing Formation (Sugai and Matsui, 1957) correspond to the Kunugidaira Formation of Hanzawa (1954). Both formations are subjacent to the Goyasu Formation and consist mainly of the graywacke type sandstone, which contains andesitic or basaltic rock fragments, intercalated with layers of coal, lignite and rhyolitic tuff. Both occupy the lowest stratigraphic position in the Yunagaya Group, and the fossils from both formations resemble each another.

Type locality: Kunugidaira, Isohara-cho, Kita-Ibaraki City, Ibaraki Prefecture.
Thickness: 65 to 100 meters.

Lithology and stratigraphic relationship: In the Iwaki North Area this formation is known only in the environs of Shichiku and Yagyu, Yotsukura-cho; it overlies the Shirasaka Formation with unconformity according to Sugai and Matsui (1957), and is concealed at Taira-Umanome, Taira-Matsukusune and the east of Onahama from the boring data (Sugai and Matsui, 1957).

In the vicinity of the Futatsushima spa, Isohara-cho, the type locality of this formation, it attains a thickness of 65 meters and overlies the Shirasaka Formation with basal conglomerate. The lower part is composed mainly of medium to coarse grained graywacke type sandstone (about 15 meters in thickness). The middle part mainly of fine grained rhyolitic tuff intercalated with layers of sandstone and tuffaceous mudstone (about 25 meters in thickness); grains of glauconite are interbedded in this rhyolitic tuff. The upper part is mainly of fine to medium grained graywacke type sandstone intercalated with layers of mudstone and lignite seams (about 20 meters in thickness). The uppermost part of the formation consists of lignite and coal seams, carbonaceous shale, and carbonaceous sandstone and mudstone with abundant remains of molluscs.

The formation is distributed from Negishi, Tono-cho to Kami-Yamada, Yamada-cho and the Kuroda basin in the Iwaki South Area. The strikes are N10° to 30°W and dips of 10°E, except of 20°E in the environs of Idosawa and N70°E to E-W strikes and dips of 10°N at Dosaka, Tono-cho.

In the vicinity of Taki, Tono-cho, the formation consists of basal conglomerate, graywacke type sandstone, shale and coal beds (the third coal bed) in upward succession. In the upper part there is a tuffaceous mudstone with marine molluscs and coal beds (the second coal bed). Coarse grained sandstone (30 cm), carbonaceous shale (20 cm thick), shale (1 m) and a coal bed (the first coal bed) overlie the second coal bed in regular sequence with conformity. The first coal bed is superposed by fine to medium grained massive graywacke type sandstone (60 m thick) which yields molluscan fossils and is intercalated with layers of mudstone and coal seams. Besides, there is a tuffaceous mudstone (5 m thick) in the uppermost part, superposed with unconformity by the basal conglomerate of the Goyasu Formation.

In the Kuroda-basin, Tabito-cho, the stratigraphic sequence is similar to that in the vicinity of Taki. The lower part is composed mainly of fine to coarse grained graywacke type sandstone intercalated with layers of tuffaceous mudstone and lignite seams, and the upper part is an alternation of pebble to cobble size conglomerate and medium to coarse grained arkose sandstone. The uppermost part consists mainly of coarse grained arkose sandstone (4 to 5 m thick).

In the Futaba Area the middle to lower part of the Kunugidaira Formation overlies the Asagai and Shirasaka formations with basal conglomerate. Generally, the lower part of the Kunugidaira consists mainly of conglomerate intercalated with conglomerate-bearing sandstone and the upper of rhyolitic tuff intercalated with rhyolite lava. The uppermost part is of tuffaceous shale and coarse grained sandstone. Conglomerate is thick in the north and thin in the south whereas rhyolitic tuff is thick in the south and thin in the north. Conglomerates are pebble (dominant) to cobble size and mainly of chert, quartz vein, slate, sandstone and amphibolite. Their shapes are subrounded but the soft rocks as mudstone are angular and were derived from the Shirasaka Formation.

The general strikes and dips of the formation are N-S to NNW-SSE and dips 40° to 70°E respectively. The Kunugidaira is influenced more strongly than the Shiramizu Group by the Futaba Flexual Belt (Tsuneishi, 1965). This formation is covered with conformity by the Goyasu Formation in this area.

Sedimentary environment and geological age: From the rock facies and fossils, it is inferred that this formation was terrestrial in the early stage, brackish in the middle stage and littoral in the later stage. As indicated by the rhyolitic tuff, volcanic activity which was not so remarkable during Shiramizu time was active in the surveyed area during the middle to later stages of this formation.

The geological age of this formation is Early to Middle Miocene from the molluscan and plant fossils. According to Tanai (1955), the plant fossils are similar to the Aniai Flora of Akita Prefecture and therefore may point to a climatic condition of the temperate zone.

2. GOYASU FORMATION (Tokunaga, 1927)

Type locality: Goyasu-bank, Taira-Matsukusune, Iwaki City, Fukushima Prefecture. Thickness: 70 to 260 meters.

Stratigraphic relation with the Kunugidaira Formation: In the Iwaki North Area, Sugai and Matsui (1957) stated that the Goyasu Formation is conformable with the Taki coal-bearing Formation (equivalent of the Kunugidaira Formation).

In the Futaba Area the Kunugidaira Formation consists of tuff, tuffaceous mudstone and pebble size conglomerates and grades upwards into the Goyasu Formation which is composed mainly of coarse grained arkose sandstone.

West of Futatsushima, Isohara-cho, the Goyasu Formation of medium to coarse grained arkose sandstone intercalated with layers of pebble to cobble size conglomerate is underlain by the Kunugidaira Formation of sandstone and mudstone with molluscan fossils with conformity.

In the Iwaki South Area the Goyasu and Kunugidaira are in conformable relationship in the environs of Shimo-Taki, Tono-cho. However, an unconformity is found elsewhere; in the environs of Taki medium grained sandstone intercalated with fine grained tuff of the Kunugidaira Formation is superposed with unconformity by the basal conglomerate (30m thick) of the Goyasu Formation. In the vicinity of Hiragoronai, Tono-cho, medium grained sandstone of the Kunugidaira Formation is covered with unconformity by the basal cobble to boulder conglomerate (10 m thick) of the Goyasu Formation. In the vicinity of Kami-Yamada, Yamada-cho, the Goyasu Formation overlies the Kunugidaira

Formation which is composed of medium grained sandstone and a lignite bed (10 to 15 cm thick). The basal part of the Goyasu Formation consists of medium to coarse grained arkose sandstone and pebble to cobble size conglomerate which contacts with the Kunugidaira Formation with rugged surface, appearing as a load-cast at first view. But, when observed in detail, the sandstone of the Goyasu Formation near the boundary with the Kunugidaira Formation contains fragments of tuffaceous mudstone and lignite which were derived from the Kunugidaira Formation. It is also considered that erosion had taken place during post-Kunugidaira and pre-Goyasu time.

Previously it was thought that the stratigraphic relation between the Kunugidaira Formation (Taki coal-bearing Formation) and the Goyasu Formation was a conformity, but the present studies show that there is a conformity in the Futaba and Iwaki North areas, but an unconformity at many localities in the Iwaki South Area. Thus, the relation between the two stratigraphic units is a partial unconformity.

Lithology and stratigraphic relation: In the Iwaki North Area the Goyasu overlies the Shirasaka Formation with clino-unconformity and grades upwards into the next younger Mizunoya Formation; the strikes and dips are N-S to NNW-SSE and 15° to 20°E respectively. The unconformity between the Shiraska Formation and the Goyasu can be observed at Joban-Shirasaka, Joban-Yumoto-machi and Shimo-Ogawa, Ogawa-cho, etc. The thickness of the basal conglomerate of the Goyasu is about one meter at Shirasaka, about 10 meters at Takasaka, about 20 meters at Taira-Furudate, about 10 meters at Sekiba, Ogawa-cho and about 100 meters in the basin of the Shimoda River. It increases its thickness towards the north suggesting in general a bay shape. The conglomerate is of cobble to boulder size and consists of granodiorite, chert, slate, and rhyolite, and mudstone which was derived from the Shirasaka Formation.

The lower part of the Goyasu is composed mainly of conglomerate-bearing (granule to pebble size) sandstone, with irregular bedding and cross-lamina, intercalated with layers of discontinuous pebble size conglomerate, coal and lignite. Especially, as found in and around Yumoto-Shirasaka, the cross-lamina, very coarse grained arkose sandstone and the irregular arrangement of the conglomerate and soft pebble conglomerate in the lowest part of the formation suggest a beach facies.

The upper part of the Goyasu, at the type locality, is composed mainly of fine to medium grained arkose sandstone interbedded with two lignite layers and some mudstone layers. The uppermost part in the environs of Taira-Yotsunami, consists of an alternation of sandstone and mudstone which grades upwards into the next younger Mizunoya Formation.

The Goyasu Formation is 50 to 140 meters in thickness in this area.

In the Iwaki South Area the general strikes and dips are N10°E to N20°W and 10° to 15°E respectively, except in the vicinities of Tabasaka and Kami-Yamada. The Goyasu overlies the Kunugidaira Formation with unconformity (a partial conformity). It forms the core of the Hirono Anticline (Ishiguri, 1968 MS) and is superposed by the Izumi Group with clino-unconformity.

The basal conglomerate is 30 meters thick at Taki, 10 meters thick at Hiragoronai and near to zero meters in thickness in the vicinity of Kami-Yamada; the thickness increases towards the northwest.

The lower part of this formation consists of conglomerate-bearing coarse grained arkose sandstone showing good development of cross-lamina intercalated with layers of conglomerate, gradually becoming fine to medium grained in the middle to upper parts. The upper part consists of fine grained sandstone with carbonate fragments and sand-pipes.

In the Futaba Area this formation shows the general strikes of N-S to NNW-SSE and dips of 50° to 70°E, being influenced by the Futaba Flexual Belt. It overlies the Kunugidaira Formation with conformity. In the environs of Hirono-cho this formation is distributed east of the Futaba thrust fault and is covered by the Izumi Group with unconformity; it forms the core of the anticline of the Futaba Fold

The Goyasu Formation consists mainly of medium to coarse grained granule to pebble size conglomerate-bearing arkose sandstone and is intercalated with layers of lignite (10 to 30 cm thick) and subrounded to subangular pebble size conglomerate, which is composed mainly of slate, sandstone, chert and rhyolitic rocks, in the lower part. There is little fine grained sandstone in the upper part of this formation in this area. The thickness of this formation is about 70 meters.

Sedimentary environment: From the rock facies and good development of cross-lamina found in the sandstone, it is considered that this formation was deposited in the littoral zone.

3. MIZUNOYA FORMATION (Tokunaga, 1927)

Type locality: Joban-Mizunoya, Iwaki City, Fukushima Prefecture. Thickness: 50 to 130 meters.

Lithology and stratigraphic relation: In the Iwaki North Area the Mizunoya with general strikes and dips of N-S to N30°W and 10°E respectively overlies the Goyasu Formation with conformity and grades upwards into the Kameno-o Formation.

At the type locality and in the vicinity of Taira-Matsukusune the Mizunoya is composed of a mudstone part in the lower part and of a sandstone part in the upper. In the environs of Taira-Furudate, Taira-Yotsunami and Taira-Midaikyo this formation consists of an alternation of mudstone and sandstone and, mudstone is dominant in the lower part and sandstone in the upper. The mudstone is micaceous and grayish black to grayish blue in color. It weathers into onion structure. The sandstone is grayish blue to yellowish brown in color and subarkose medium grained sandstone, well sorted and with hard sandstone and marly concretions.

In the vicinities of Taira-Kami-Arakawa and Joban-Mizunoya medium grained sandstone intrudes the mudstone layers along joints as clastic dikes. This phenomenon is inferred to have been formed by tectonic control after deposition of the formation (Mitsui, 1967 MS).

In the Iwaki South Area this formation lies upon the Goyasu Formation with conformity and grades upwards into the next younger Kameno-o Formation. The Mizunoya Formation is overlain by the Nakayama Formation with unconformity at the northwest of Miyamaguchi, Tono-cho.

In this South Area the Mizunoya consists of an alternation of mudstone and sandstone and in general, mudstone is dominant in the lower part and an alternation with strata of equal thickness in the middle to upper parts. The formation in the environs of Miyamaguchi, Tono-cho is subdivided into the mudstone part in the lower and the sandstone part in the upper. The general strikes and dips are N-S to N30°W and 10°E respectively, and the thickness ranges from 80 to 100 meters.

In the Futaba Area the general strikes and dips of this formation are N-S to NNW-SSE and dips of 50° to 80°E or W respectively, being influenced by the Futaba Flexual Belt. The formation is about 80 meters in thickness and composed mainly of tuffaceous mudstone intercalated with the layers of sandstone near the boundary with the Goyasu Formation. The lower part consists of an alternation of sandstone and mudstone and of grayish blue colored mudstone in the middle to upper parts.

Sedimentary environment and geological age: Hanzawa (1957) stated that the formation yielded *Conchocele nipponica*, *C. bisecta*, *Lucinoma otukai*, *Macoma optiva* and

Turritella (*Hataiella*) *omurai* and is thus Miocene in age. He also stated (Hanzawa, *Op. cit.*) that the marine transgression of the Miocene age began at this time in real earnest and was deposited under a cold climate. On the other hand, from the remains of diatom fossils, Ishiguri (1968 MS) stated that the age may correspond to the Onnagawa stage in the Oga Peninsula, Akita Prefecture.

Judged from the lithology and the fossils, the marine transgression of the Yunagaya Group, which begun with the Goyasu Formation was deposited in the neritic zone. Judged from the layers of medium to coarse grained sandstone interbedded in the mudstone layers and that both layers form an alternation, it is thought that small scale fluctuations occurred during deposition of this Formation.

4. KAMENO-O FORMATION (Iwai, 1950)

Type locality: Kameno-o, Joban-Mizunoya, Iwaki City, Fukushima Prefecture. Thickness: 90 to 140 meters.

Lithology and stratigraphic relation: In the Iwaki North Area, in the environs of the type locality and Taira-Ososawa, the Kameno-o Formation lies upon the Mizunoya Formation and is overlain by the Kamiyata Sandstone Member of the Taira Formation with conformity. The general strikes and dips are N20° to 30°W and 10°E respectively. The thickness is from 90 to 120 meters. On the other hand, in the vicinity of Mt. Ishimori-yama this formation overlies the Mizunoya Formation and is superposed by the Ishimoriyama Tuff-breccia Member of the Taira Formation with conformity and the general strikes and dips are N-S and 15° to 20°E respectively.

The Kameno-o consists mainly of purplish gray stratified shale intercalated with layers of coarse grained subarkose sandstone (10 cm to 5–6 m thick). The shale is generally purplish gray and siliceous in this North Area. Molluscan fossils occur throughout the shale.

In the Iwaki South Area this formation overlies the Mizunoya Formation with conformity and grades upwards into the Kamiyata Sandstone Member, but in the area of Kadono, Tono-cho, it is covered with the Nakayama Formation with unconformity. The general strikes and dips are N20°–30°W and 15°E respectively, but change to E-W near the Yamada fault. The thickness of the formation attains 30 meters at Kawabata, 100 meters at Kadono, 120 meters at Ebata and, on a whole, is thicker towards the southeast and thinner to the northwest. From this, it is presumed that the transgression of the Yunagaya Group was from to southeast.

The basal part of the formation consists of grayish white, coarse grained arkose sandstone; the sandstone attains a thickness of 3–4 meters in the environs of Kadono and becomes thinner towards the southeast where it thins out. The upper part of this sandstone is composed of purplish gray, stratified and laminated shale with abundant remains of molluscs, fish scales and diatoms. The upper part of the formation consists of an alternation of sandstone and shale (dominant) and shows intraformational abnormal deposition (Iwai, 1953), that is, intraformational folding, load-cast and slumping structures, etc.

In the Futaba Area this formation is 135 meters in thickness. It is distributed from Naraha-cho to the vicinity of Hisanohama, Hisanohama-cho. It lies upon the Mizunoya Formation and grades upwards into the Honya Mudstone Member of the Taira Formation, both with conformity. The general strikes are NNW-SSE and dips are 60° to 80°E or W.

The formation is composed of purplish gray stratified and laminated shale with the remains of molluscs and intercalated with layers of medium to coarse grained subarkose sandstone attaining a thickness of 0.3–2 meters in the middle and upper parts, which form the alternation. Contemporaneous conglomerates and conglomerates derived from the basement rocks are interbedded in this sandstone. In the alternation of shale and sandstone in the middle and upper parts of the formation there occur intraformational abnormal deposition (Iwai, 1953).

Sedimentary environment and geological age: From the lithological and paleontological evidences, this formation is inferred to have been deposited in a stagnant sea area of the open sea in the Middle Miocene. Thus, it is considered that the Formation was deposited in a sea deeper than that in which the Mizunoya was deposited. The marine transgression of the Yunagaya Group reached the maximum during this stage. The existence of thick layers of medium to coarse grained sandstone and intraformational abnormal deposition suggest that small scale movements occurred during deposition of this formation.

5. TAIRA FORMATION (Tokunaga, 1927)

From lithology this formation can be subdivided into the Kamiyata Sandstone Member, the Ishimoriyama Tuff-breccia Member, the Honya Mudstone Member and the Misawa Sandstone Member in upward succession. It overlies the Kameno-o Formation with conformity. The first two members just mentioned belong to the same stratigraphic horizon. The Honya Mudstone Member exists in a horizon corresponding to the lower part of the Misawa Sandstone Member with which it interfingers.

5-1. KAMIYATA SANDSTONE MEMBER (Sugai and Matsui, 1953)

Type locality: Taira-Kamiyata, Iwaki City, Fukushima Prefecture. Thickness: 30 to 65 meters.

Lithology and stratigraphic relation: This Sandstone Member is distributed only in the south of Taira of the Iwaki North Area and the Iwaki South Area and does not extend to the Futaba Area. At the north of Taira the Ishimoriyama Tuff-breccia Member replaces this Member.

This Sandstone Member lies on the Kameno-o Formation with conformity and grades upwards into the Honya Mudstone Member. The general strikes and dips are N-S to NNW-SSE and 10°–20°E respectively, but they change to N70°E to E-W and 10°N in the area of Onahama. The thickness is 30–65 meters.

The Kamiyata Sandstone Member is a conspicuous sandstone deposit between the Kameno-o Formation and the Honya Mudstone Member and is an important key bed for the stratigraphy of the Yunagaya Group.

This Sandstone Member consists of yellowish brown, medium to coarse grained subarkose sandstone intercalated with shale similar to that of the Kameno-o Formation in the lower part and with mudstone resembling the Honya Mudstone Member in the upper part. This Sandstone Member makes an alternation of sandstone and mudstone at Hashirikuma, Kashima-cho and at the northwest of Takishiri, Izumi-cho. There are jagger patches of coarse grained sandstone, hard sandstone concretions and convolute structures in this sandstone.

5-2. ISHIMORIYAMA TUFF-BRECCIA MEMBER (Watanabe, 1934)

Type locality: Mt. Ishimori-yama, Taira, Iwaki City, Fukushima Prefecture. Thickness: 100 meters.

Lithology and stratigraphic relation: This Tuff-breccia Member is distributed only in the Iwaki North Area, namely, from Komagome, Yotsukura-cho to the vicinity of Taira and overlies the Kameno-o Formation with conformity.

This Member is composed mainly of boulder size (the maximum is 2–3 meters in diameter) andesitic to basaltic tuff breccia or agglomerate intercalated with lenses of andesitic to basaltic volcanic sandstone of about one meter in thickness in the upper part.

5-3. HONYA MUDSTONE MEMBER (Sugai and Matsui, 1953)

Type locality: Honya, Izumi-cho, Iwaki City, Fukushima Prefecture. Thickness: 100 to 200 meters.

Lithology and stratigraphic relation: In the environs of Mt. Ishimori-yama in the Iwaki North Area this Mudstone Member overlies the Ishimoriyama Tuff-breccia Member with conformity and is overlain by the Misawa Sandstone Member with conformity or interfingering. The general strikes and dips are N20°–40°W and 10° to 15°E respectively. On the other hand, in the vicinities of Mizunoya-Kameno-o and Taira-Ososawa this Member lies on the Kamiyata Sandstone Member with conformity and is covered by the Misawa Sandstone Member with conformity or interfinger with N20° to 30°W strikes and 10° to 15°E dips. In the vicinity of Honya, Izumi-cho, the type locality, the topmost part of the Honya Mudstone Member interfingers with the Misawa Sandstone Member. The strikes and dips of this Member are WNW-ESE, through E-W to WSW-ENE and dips of 10° to 20°N in the area of Onahama. The thickness is from 50 to 200 meters.

In the Iwaki South Area this Mudstone Member is distributed only in the south of Kami-Kamado, Watanabe-cho and its general strikes is N-S to N30°W and dips 10° to 20°E. This Member lies on the Kamiyata Sandstone Member with conformity and is superposed by the Nakayama Formation with unconformity.

In the Futaba Area this Member is distributed from Sekinoue, Hirono-cho to Hisanohama with the strikes of N-S to NNW-SSE and dips of 60° to 80°E, and was influenced by the Futaba Flexual Belt. The Member, 100 to 150 meters in thickness, directly overlies the Kameno-o Formation with conformity. The Kamiyata Sandstone and Ishimoriyama Tuff-breccia members are not distributed in this area.

The lower part of the Honya Mudstone Member in the surveyed area is composed of an alternation of mudstone (dominant) and sandstone. The middle to upper parts consists of massive mudstone with molluscan and foraminiferan remains and lenses of andesitic to basaltic tuff and breccia of the Ishimoriyama Tuff-breccia Member.

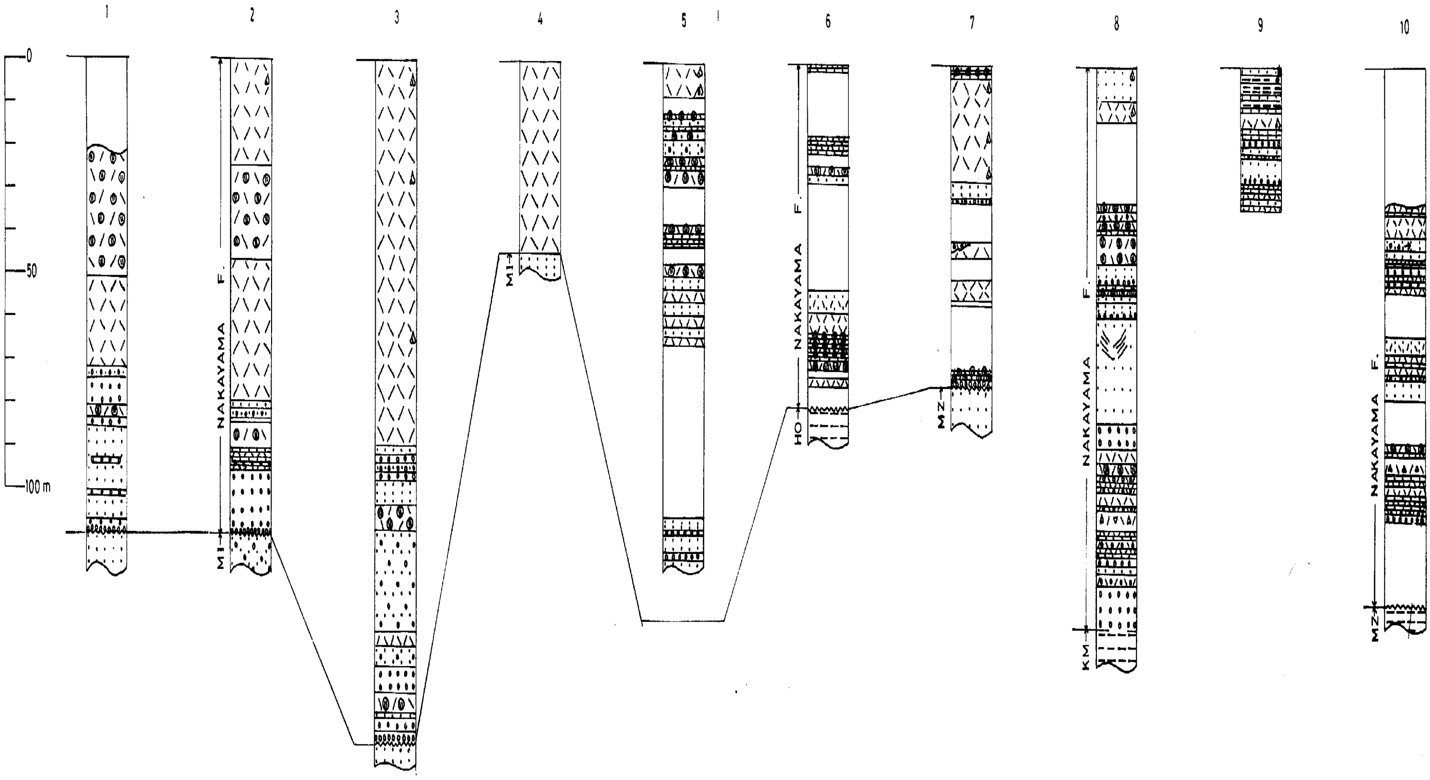
Sedimentary environment and geological age: It is thought that this Mudstone Member represents a regressive facies, first, because there is no stratigraphic break between the Kameno-o Formation and this Member, and second, because the underlying Kameno-o Formation from plaeontological and lithological evidences is a stagnant sea facies, contrary to the shallow water facies of this Member. The age of this Member is Middle Miocene according to Kamada (1962). Saito (1963), and Asano and Takayanagi (1965) from the foraminifers stated that the Honya Mudstone Member is correlative with a zone below the *Globorotalia menardii/Globigerina nepenthes* zone and with the Funakawa stage in the Oga Peninsula, Akita Prefecture.

5-4. MISAWA SANDSTONE MEMBER (Sugai and Matsui, 1953)

Type locality: Misawa, Kashima-cho, Iwaki City, Fukushima Prefecture. Thickness: 200 to 300 meters.

Lithology and stratigraphic relation: In the Iwaki North Area, the general strikes and dips of this Sandstone Member are N20°–40°W and dips of 10°–25°E or W, but in the Onahama area they change to N70°W, through E-W to N70°E, and 20°–25°N. This Member forms a gentle fold structure, but the strikes and dips are not so disturbed. It attains a thickness of 50–150 meters at the type locality, 210 meters in the environs of the Taira Station, 300 meters at Taira-Ososawa, 100–150 meters at the west of Taira-Yamaguchi and 100 meters in the vicinity of Ena. It is considered that the differences in thickness are based on the differences of the degree of overlapping with the Honya Mudstone Member.

In the environs of Taira-Izumisaki the lower 20 meters of the Member makes an alternation with the Honya Mudstone Member, the middle 30 meters consists of pebble to



1 : YOTSUNAMI—KATAYORI—IZUMISAKI
2 : SHIMOARAKAWA—NAKAYAMA—BABA
3 : KAMIYAMAGUCHI—SUGAYA
4 : ENA
5 : KAMIKAMADO—KOTSUNAGI
6 : EBATA—NAKAKAMADO
7 : TAKI—MIYAMAGUCHI
8 : KADONO—KOBUCHI
9 : ORIMATSU—NARISAWA
10 : KAWABATA—NARISAWA

MI: MISAWA SANDSTONE MEMBER
HO: HONYA MUDSTONE MEMBER
KM: KAMENO-O F.
MZ: MIZUNOYA F.

Fig. 7. Columnar sections of the Nakayama Formation

granule size conglomerate-bearing coarse grained arkose sandstone and the upper 50 meters of coarse grained arkose sandstone, and is covered by the Nakayama Formation with basal conglomerate.

In the vicinities of the Taira Station and Taira-Ososawa the lower part of the Member forms an alternation with the Honya Mudstone Member and the middle to upper parts comprises conglomerate-bearing coarse grained arkose sandstone intercalated with thin layers of fine grained tuff, mudstone, lignite and tongues of andesitic to basaltic sandy tuff-breccia of the Ishimoriyama Tuff-breccia Member.

At the type locality and the environs of the old Joban City this Sandstone Member consists almost of conglomerate-bearing coarse grained arkose sandstone interbedded with thin layers of granule to cobble size conglomerate and mudstone.

The Misawa Sandstone Member is not distributed in the Iwaki South Area.

In the Futaba Area the Member is composed mainly of granule to pebble size conglomerate-bearing medium to coarse grained arkose sandstone showing the good development of cross-bedding and the general strikes and dips are N-S and 60°–70°E, being influenced by the Futaba Flexual Belt. Along the coast from Yūsuji to Hisanohama the Member is superposed by the Nakayama Formation with unconformity.

The Misawa Sandstone Member is composed mainly of conglomerate-bearing coarse grained arkose sandstone, a lithofacies typical of a regressive phase.

NAKAYAMA FORMATION (Hanzawa, 1954), (Fig. 7)

Type locality: Taira-Nakayama, Iwaki City, Fukushima Prefecture. Thickness: about 200 meters.

Lithology and stratigraphic relation: In the Iwaki North Area this formation is distributed throughout the whole area in narrow belt form. The general strikes and dips are N20°– 40°W and 10°–15°E, but they change to N70°W ,through E-W, to N70°E and dips of 15°– 20°N. The formation is thickest in the vicinity of Taira-Nakayama, attaining 100–150 meters, it thins towards both north and south of Taira-Nakayama.

This formation overlies the Misawa Sandstone Member with partial unconformity, for example, in the vicinities of Taira-Nakayama and Taira-Kami-Yamaguchi it overlies the Misawa Sandstone Member with basal conglomerate. The lower part of this formation consists of conglomerate or of an alternation of conglomerate and conglomerate-bearing coarse grained sandstone intercalated with thin layers of fine grained tuff and pumice tuff. The conglomerate consists of andesite, basalt, chert, slate and granite and conglomerates of andesite and basalt are dominant. The upper part is composed of pumice tuff, sandy tuff and fine grained tuff with abundant remains of molluscan fossils; fine grained tuff becomes dominant towards the south. The laminations in the fine grained tuff is characteristic of water laid sediments. Southwest of Taira-Sugaya an irregular alternation of conglomerate and conglomerate-bearing sandstone of this formation lies with conformity upon the coarse grained sandstone of the Misawa Sandstone Member.

In the Iwaki South Area this formation overlies, successively from northwest to southeast, the Goyasu, Mizunoya and Kameno-o formations and the Honya Mudstone Member with unconformity and is covered by the Takaku Group with unconformity.

The basal conglomerate of the Nakayama Formation is 30 meters thick at Shimotonai, Tono-cho, 50 meters at Kano, Tono-cho, 20 meters at Miyamaguchi, Tono-cho and 12 meters at Naka-Kamado, Watanabe-cho and is, in general, thicker in the northwest and thinner towards the southeast. The conglomerate consists mainly of subrounded to subangular well sorted andesite or basalt (60 to 80%) besides schist, amphibolite, chert, quartz diorite and granodiorite. The middle part of the formation is composed mainly of conglomerate-bearing sandstone and fine grained tuff intercalated with layers of conglomerate and pumice tuff. The upper part consists of fine grained rhyolitic tuff and tuffaceous sandstone intercalated with thin layers of pumice tuff and has yielded molluscan and plant fossils.

In the Futaba Area this formation (20 m thick) is distributed between Yusuji and Hisanohama with strikes of NNW-SSE. It is composed of basal conglomerate which comprises conglomerate of andesite and basalt, etc.

Sedimentary environment: The lower part of the Nakayama consists of conglomerate and conglomerate-bearing sandstone changing upwards into fine grained facies, thus showing cyclic sedimentation. Volcanic activity occurred during deposition of the formation, as inferred from that the conglomerate is composed mainly of andesite and basalt, and that thick rhyolitic tuff is interbedded in the middle to upper parts. From the climatic conditions indicated by the molluscan and plant fossils, it is considered that the formation (200 m thick) was deposited accompanying volcanic activity under a warm climate and in the neritic zone.

It is thought that the Yunotake fault was responsible for dividing the investigated area into two smaller sedimentary basins, viz., into the Iwaki North Area and the Iwaki South Area, for two reasons, the first is because the Nakayama Formation lies upon the Misawa Sandstone Member with partial unconformity in the Iwaki North Area and, overlies, successively from southeast towards the northeast, the Honya Mudstone Member, the Kameno-o, Mizunoya and Goyasu formations with unconformity, and second, because *Vicarya* which is abundant in the Iwaki South Area is unknown from the Iwaki North Area. Judged from that the sediments become thicker towards the center of the Iwaki and Kamamae synclinal basins, it is inferred that basinal movements occurred during deposition of the Nakayama Formation.

TAKAKU GROUP (Sugai and Matsui, 1953), (Fig. 8)

The name was proposed for the so-called Taga Group distributed mainly in the Iwaki North Area, retaining the name of Taga Group for the rocks distributed in the Iwaki South and Futaba Areas, because the groups can be distinguished from one another by stratigraphy and geological structure. On the other hand, Hanzawa (1957) held the view that the Takaku and Taga groups are of the same horizon and thus adhered to the old name of Taga Group. The writer follows Sugai and Matsui (1953, 1957) and uses the name of Takaku Group.

The Takaku Group is distributed in the Iwaki North Area and the Iwaki South Area but not in the Futaba and Taga areas. This Group lies on the Nakayama Formation with unconformity and is superposed by the Izumi Group with unconformity. It is subdivided into the Kamitakaku, Kamikamado, Numanouchi and the Shimotakaku formations, in upward succession. The Kamikamado Formation is distributed only in the Iwaki South Area and is correlated with the Kamitakaku and Numanouchi formations of the Iwaki North Area.

The Takaku shows cyclic sedimentation, comprising coarse grained conglomerate-bearing sandstone (the Kamitakaku and Kamikamado formations), fine grained sandstone (the Numanouchi Formation) and tuffaceous siltstone (the Shimotakaku Formation) in upward sequence. In the Iwaki North and Iwaki South areas there is difference in the overlapping of the strata, and therefore also in their sedimentation, probably influenced in part by the activation of the Yunotake fault.

1. KAMITAKAKU FORMATION (Iwai, 1950)

The Kamitakaku Formation was proposed by the Institute of Geology and Paleontology, Tohoku University and introduced by Iwai (1950).

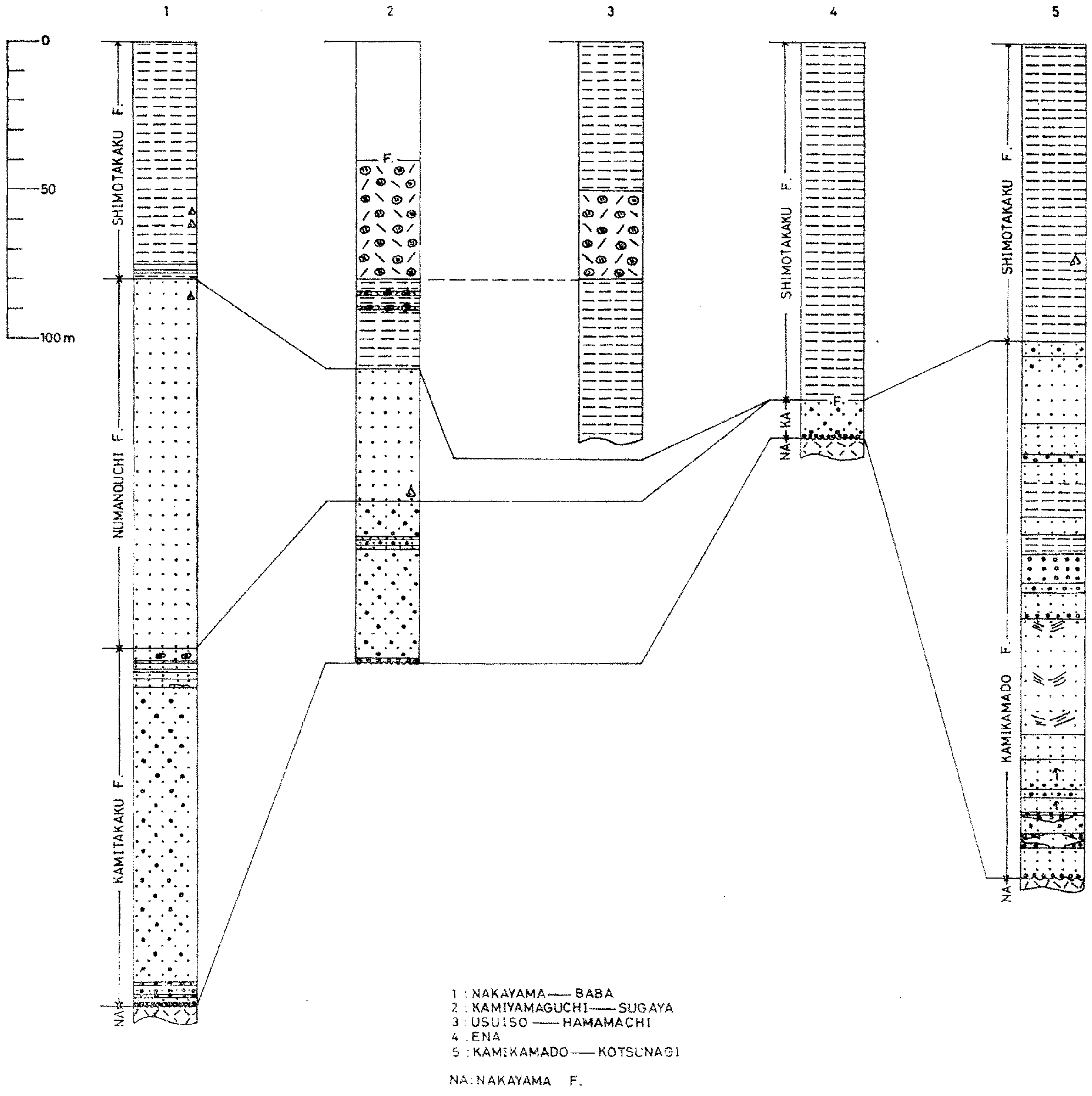


Fig. 8. Columnar sections of the Takaku Group

Type locality: Taira-Kami-Takaku, Iwaki City, Fukushima Prefecture. Thickness: 50–120 meters.

Lithology and stratigraphic relation: This formation is distributed in the south of the old Taira City of the Iwaki North Area in narrow belt form and also partly in the vicinity of Nagatomo, Yotsukura-cho. It lies on the Nakayama Formation with disconformity; its strikes and dips are N20° to 40°W and 10° to 15°E at Taira-Shimo-Yamaguchi, N60°–70°W with dips of 10°–15°N at Taira-Sugaya and of WNW-ESE,E-W, WSW-ENE and dips of 10°–15°N between Kubo, Kashima-cho and Ena.

The Kamitakaku consists mainly of coarse grained conglomerate-bearing sandstone intercalated with layers of fine grained tuff and conglomerate. The conglomerate is rather well sorted, of granules to cobbles of the basement rocks and andesite. The sandstone is yellow to grayish brown, micaceous, and quartz bearing, coarse grained massive sandstone with pumice. Sugai and Matsui (1957) reported *Pecten kimurai* Yokoyama, *Ostrea* sp., *Juglans* sp., *Fagus* sp. (cf. *Japonica*), *Betula* sp., *Zelkova Ungeri* from the basal part of this formation.

Sedimentary environment: It is considered that the formation was deposited in the littoral zone, for three reasons. the first is because the molluscan fossils from the superjacent Numanouchi Formation are those of the neritic zone, second, because this formation consists mainly of conglomerate-bearing coarse grained sandstone, and third, because plant fossils occurred from this formation.

2. KAMIKAMADO FORMATION (Ishiguri, 1968 MS)

The Kamikamado Formation was named by Ishiguri (1968 MS) for the lower to middle parts of the Takaku Group in the Iwaki South Area. Sugai and Matsui (1957) treated the middle to lower parts of the Takaku Group distributed in the Iwaki South Area as the "Kamitakaku+Numanouchi" Formation. Ishiguri (1968 MS) pointed out that such a procedure is not desirable because the formation in the Iwaki South Area consists mainly of the Kamitakaku Formation and a part of the Numanouchi Formation. Following Ishiguri (1968 MS), the writer uses the Kamikamado Formation to include the upper part of the Nakayama Formation and the lower part of the Shimotakaku Formation.

Type locality: Kami-Kamado, Watanabe-cho, Iwaki City, Fukushima Prefecture. Thickness: 180 meters.

Lithology and stratigraphic relation: This formation is distributed only in the Iwaki South Area, that is, between Aoya and Matsugoya and the environs of Osawa, all in Watanabe-cho. It lies on the Nakayama Formation with para-unconformity and is overlain by the Shimotakaku Formation with conformity. The formation has the same geologic structure as the underlying Nakayama Formation. The general strikes and dips are N-S to N30°W and about 10°E in the western wing of the basin and N-S to N30°W and 10° to 40°W in the eastern wing.

The lowest part of the formation comprises basal conglomerate (about 2 m thick), and the middle to lower part mainly of yellowish brown arkose and graywacke type conglomerate-bearing grained sandstone intercalated with thin layers (20 to 50 cm) of conglomerate showing good development of irregular lamination and cross lamination. The conglomerates are of pebble to cobble size, rounded and comprise schist, chert, granodiorite and andesite, and, pebble conglomerates of fine grained tuff derived from the Nakayama Formation. The middle to upper parts consists of coarse to fine grained sandstone intercalated with layers of conglomerate and mudstone; it also contains mica and pumice. The fine grained sandstone closely resembles that of the Numanouchi Formation.

Sedimentary environment: This formation is a coarse grained facies in the lower part but becomes fine grained towards the upper part. Hence, from lithology it is considered that this formation was deposited in the littoral zone in the early stage and in the neritic zone towards the upper part.

3. NUMANOUCHI FORMATION (Iwai, 1950)

This formation name was proposed by the Institute of Geology and Paleontology, Tohoku University and introduced by Iwai (1950).

Type locality: Taira-Numanouchi, Iwaki City, Fukushima Prefecture. Thickness: 125 meters.

Lithology and stratigraphic relation: The Numanouchi Formation is distributed in the south of Taira-Kami-Takaku and attains 125 meters in maximum thickness, averaging about 30–80 meters. It overlies the Kamitakaku Formation with conformity and grades upwards into the next younger Shimotakaku Formation; the general strikes and dips are N40° to 60°W and 10° to 15°E, with the exception of N70°E to E-W and dips of 10°N in the area of Kashima-cho.

This formation is composed mainly of pale green, massive, fine grained sandstone intercalating marly concretions with well preserved molluscan fossils. The molluscan fossils occur throughout the sandstone.

Sedimentary environment: This formation is inferred to have been deposited in the neritic zone from the following reasons, 1) the lithology of this formation is finer than that of the Kamitakaku Formation, and 2) the molluscan remains from the formation are shallow water species (Hatai and Kamada, 1950; Kamada, 1962).

4. SHIMOTAKAKU FORMATION (Sugai and Matsui, 1953)

Type locality: Taira-Shimo-Takaku, Iwaki City, Fukushima Prefecture. Thickness: 80 to 140 meters.

Lithology and stratigraphic relation: In the Iwaki North Area this formation is distributed between Taira-Shimo-Takaku and Taira-Usuiso in narrow belt form and in the environs of Kuramochi, Kashima-cho, in arc shape in the south of the Shirasaka fault. The general strikes and dips are N40° to 60°W and 10°N respectively. It overlies the Numanouchi Formation with conformity.

In the Iwaki South Area the formation is distributed only in the vicinity of Aoya, Watanabe-cho and attains a thickness of 100 meters. The general strikes and dips are N20°W to N30°E and dips of 10°E or W. The formation lies on the Kamikamado Formation with conformity and is superposed by the Nakosonoseki Formation of the Izumi Group with clino-unconformity. The Shimotakaku is subdivided into the Kamiyasaku Tuffaceous Siltstone, the Usuiso Pumice Tuff and the Hamamachi Tuffaceous Siltstone members in upward succession.

Sedimentary environment: It is thought that the maximum transgression of the Takaku Group was during deposition of this formation, because of the lithology.

4-1. KAMIYASAKU TUFFACEOUS SILTSTONE MEMBER (Sugai and Matsui, 1953)

Type locality: Taira-Kamiyasaku, Iwaki City, Fukushima Prefecture. Thickness: about 140 meters.

This Member occupies a large part of the Shimotakaku Formation in both thickness and distribution. It lies with conformity upon the Numanouchi Formation.

In the Iwaki North Area this Member consists of massive tuffaceous siltstone intercalated with thin layers of fine to medium grained tuffaceous sandstone and shows good development of stratification towards the upper part.

In the Iwaki South Area the lower part of the Member consists of dark blue, fine grained sandstone with well developed laminations. The middle to upper parts of the massive tuffaceous and sandy siltstone yield abundant fragments of pumice and plant fossils. Molluscan and crab fossils occurred from the member (Ishiguri, 1968 MS).

4-2. USUISO PUMICE TUFF MEMBER

This member is the same as the Usuiso Sandstone Member of Sugai and Matsui (1953).

Type locality: Taira-Usuiso, Iwaki City, Fukushima Prefecture. Thickness: 40 meters

This Member is distributed in the vicinity of Taira-Usuiso and in the east of Taira-Sugaya in narrow belt form and consists of pumice tuff. It overlies the Kamiyasaku Tuffaceous Siltstone Member with conformity.

4-3. HAMAMACHI TUFFACEOUS SILTSTONE MEMBER (Sugai and Matsui, 1953)

Type locality: Taira-Hamamachi, Iwaki City, Fukushima Prefecture. Thickness: about 50 meters.

It lies with conformity upon the Usuiso Pumice Tuff Member, and makes an alternation of well stratified tuffaceous siltstone, sandstone and pumice tuff.

IZUMI GROUP (Fig. 9)

The Izumi Group is correlated with the Taga Group by Sugai and Matsui (1957). The name of Taga Group had been used variously by authors (Table 1), and to avoid confusion in stratigraphic nomenclature, the writer proposes to use the name of Izumi Group for the Taga Group of Sugai and Matsui (1957) distributed in the area studied. Also, from the view of stratigraphic nomenclature of the Izumi Group the writer proposes the new formation names of Nakosonoseki, Kurosuno and Sekinoue in upward succession.

The Izumi Group lies with unconformity upon the Takaku Group; the differences are, 1) their lithofacies are different (the tuffaceous siltstone of the Shimotakaku Formation of the Takaku Group is hard and near to fine grained tuff, whereas that of the Izumi Group is soft and near to mudstone), and *Makiyama* (=*Sagarites*) which is common in the Izumi Group was not be found in the Takaku Group, 2) as pointed by Sugai and Matsui (1957), the Tabasaka fault, one of the main faults, and the ones associated therewith cut the rocks of the Takaku Group, but not those of the Izumi Group, 3) the Takaku Group joins in construction of the Kamamae Syncline and Hiruno Anticline (Ishiguri, 1968 MS), whereas the Izumi Group lies with angular unconformity upon the Yunagaya Group and the Nakayama Formation and erosion cut deeply to the core of the Hiruno Anticline before deposition of the Izumi, and, 4) the joints in the Takaku Group are of both shear joints and tension joints, whereas those in the Izumi Group are only tension joints.

The Izumi Group is subdivided into the Nakosonoseki, Kurosuno and Sekinoue formations in upward succession.

1. NAKOSONOSEKI FORMATION

The Nakosonoseki Formation is correlated with the Iwamoto Formation of Eguchi and Suzuki (1953), the Takahagi Formation of Sugai and Matsui (1957) and the Futatsushima Formation of Eguchi and Suzuki (1953).

Type locality: Nakosonoseki, Nakoso-cho, Iwaki City, Fukushima Prefecture. Thickness: 30–40 meters.

Lithology and stratigraphic relation: This formation is distributed in the vicinities of Nakosonoseki, Nakoso-cho and Iwama, Ueda-cho and between Hora and Otsurugi, Izumi-cho. It lies on the Kameno-o Formation almost with clino-unconformity. The basal conglomerate is of cobble to boulder size and consists of chert, slate, sandstone and muddy rocks, the latter two being derived from Tertiary formations.

This formation is composed mainly of fine to medium grained arkose and tuffaceous sandstone intercalated with layers of mudstone and soft rock (mudstone) conglomerate of granule to pebble size. The mudstone is dark gray and contains pumice, carbonaceous fragments and abundant remains of *Makiyama* (=*Sagarites*). This formation grades upwards into the next younger Kurosuno Formation.

Table 1. Correlation table in the Joban coal-field

Kamada, Y. (1949 MS) (Taira-Onahama area)	Nakajima, H. (1953 MS) (Yamada-Kadono area)	Hanzawa, S. (1954, 1957) (Joban Coal Field)	Sugai & Matsui (1957) (Joban Coal Field)	Iwao & Matsui (1961) (Taira & Kawamae)	Kamada, Y. (1962) (Joban Coal Field)	Mitsui, S. (1967 MS) (Middle & Northern parts of Iwaki City)	Ishiguri, I. (1968 MS) (Tono-cho)	Mitsui, S. (1970) (Joban Coal Field)
			Pleist. – Sodetama F. / Tatsuta F.	Pleist. – Sodetamayama F.		Pleist. – Sodetamayama F.		Pleist. – Sodetamayama F.
								?Pliocene – Yamadahama F.
		Pliocene – Iwasawa F.	Later Miocene–Pliocene, Taga G. – Tomioka F.	Miocene, Taga G.	Pliocene – Futaba-Tomioka F.		?Pliocene? – Ueda F.	?Pliocene, Izumi G. – Sekinoue F.
			Later Miocene–Pliocene, Taga G. – Hirono F.					Izumi G. – Kurosuno F.
								Izumi G. – Nakosonoseki F.
Lower Miocene–Middle Miocene, Toyoma G. – Kamiyasaku sandy shale F.	Lower Miocene–Middle Miocene, Taga G. – Kokozura F.	Miocene, Taga G. – Shimotakaku F. / Kokozura F.	Takaku G. – Shimotakaku F.	Takaku G. – Shimotakaku F.	Early Miocene–Middle Miocene, Taga G. – Shimotakaku F. / Kokozura F.	Miocene, Takaku G. – Shimotakaku F. / ?Kokozura F.?	Miocene, Aoya G. – Shimotakaku F.	Miocene, Takaku G. – Shimotakaku F.
Toyoma G. – Numanouchi sandstone F.		Taga G. – Numanouchi F.	Takaku G. – Numanouchi F.	Takaku G. – Numanouchi F.	Taga G. – Numano-uchi F.	Takaku G. – Numano-uchi F.	Aoya G. – Kamikamado F.	Takaku G. – Numanouchi F. / Kd F.
Toyoma G. – Kamitakaku F.		Taga G. – Kamitakaku F.	Takaku G. – Kamitakaku F.	Takaku G. – Kamitakaku F.	Taga G. – Kami-takaku F.	Takaku G. – Kami-takaku F.		Takaku G. – Kamitakaku F.
Shirado G. – Nakayama tuff & shale F.	Shirado G. – Nakayama F.	Nakayama F.	Early Miocene–Middle Miocene, Shirado G., Na F. – Minamishirado Tuff M. / Yoshinoya cg-sst. M.	Shirado G., Na F. – Mn Tuff & Mudst. M. / Yo cg & sst. M.	Shirado G. – Nakayama F.	Nakayama F.	Nakayama F.	Nakayama F.
Shirado G. – Misawa sandstone F.		Misawa F.	Yunagaya G., Taira F. – Misawa sst. M.	Yunagaya G., Taira F. – Misawa sst. M.	Yunagaya G. – Misawa F.	Yunagaya G., Taira F. – Misawa sst. M.		Yunagaya G., Taira F. – Misawa sst. M.
Yunagaya G. – Honya mudstone F. / (Ky. M.) / Is M.		Yunagaya G. – Honya F.	Taira F. – Honya mudst. M. / Ky. M. / Is. M.	Taira F. – Honya Mudst. M. / Ky M. / Is M.	Yunagaya G. – Honya F.	Taira F. – Honya mudst. M. / Ky M. / Is M.	Honya F.	Taira F. – Honya mudst. M. / Ky. M. / Is. M.
Yunagaya G. – Kameno-o shale F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.	Yunagaya G. – Kameno-o F.
Yunagaya G. – Mizunoya sst. & sh. F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.	Yunagaya G. – Mizunoya F.
Yunagaya G. – Goyasu sst. F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.	Yunagaya G. – Goyasu F.
	Yamada F.	Kunugidaira F.	Taki coal bearing F.	Taki coal bearing F.	Kunugidaira F.		Taki coal bearing F.	Kunugidaira F.
Oligocene, Shiramizu G. – Shirasaka shale F.	Oligocene, Shiramizu G. – Iwaki F.	Oligocene, Uchigo G. – Shirasaka F.	Oligocene, Shiramizu G. – Shirasaka F.	Oligocene, Shiramizu G. – Shirasaka F.	Oligocene, Uchigo G. – Shirasaka F.	Oligocene, Shiramizu G. – Shirasaka F.	Oligocene, Uchigo G. – Shirasaka F.	Eocene–Oligocene, Shiramizu G. – Shirasaka F.
Shiramizu G. – Asagai sst. F.		Uchigo G. – Asagai F.	Shiramizu G. – Asagai F.	Shiramizu G. – Asagai F.	Uchigo G. – Asagai F.	Shiramizu G. – Asagai F.	Uchigo G. – Asagai F.	Shiramizu G. – Asagai F.
Shiramizu G. – Iwaki sst. F.		Uchigo G. – Iwaki F.	Shiramizu G. – Iwaki coal bearing F.	Shiramizu G. – Iwaki coal bearing F.	Uchigo G. – Iwaki F.	Shiramizu G. – Iwaki F.	Uchigo G. – Iwaki F.	Shiramizu G. – Iwaki F.
Shiramizu G. – Shiramizu coal bearing F.		Uchigo G. – Shiramizu F.			Uchigo G. – Shiramizu F.			

F.: Formation G.: Group M.: Member

Is M.: Ishimoriyama Tuff-breccia Member Ky M.: Kamiyata Sandstone Member

Mn: Minamishirado Na: Nakayama Kd: Kamikamado

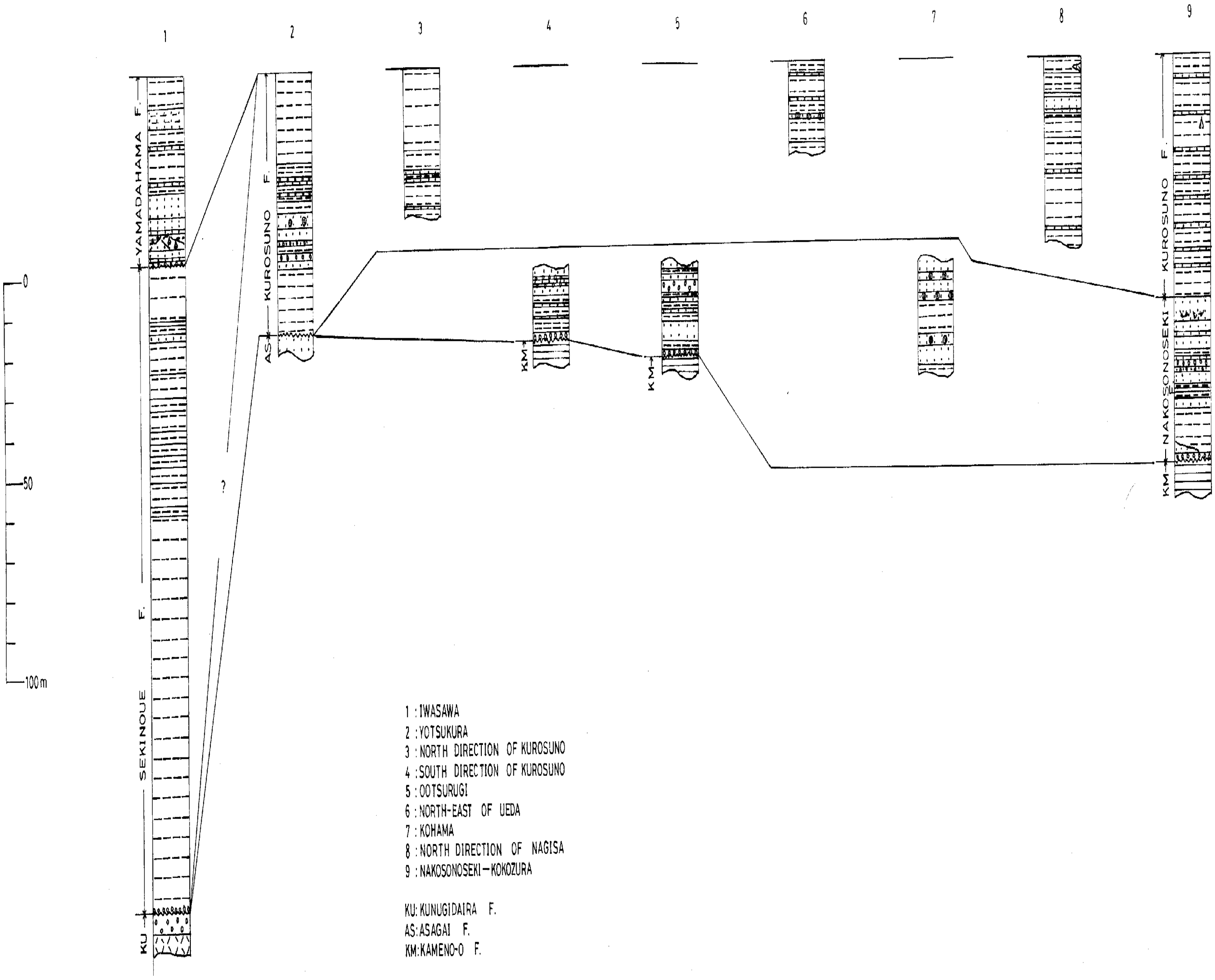


Fig. 9. Columnar sections of the Izumi Group and Yamadahama Formation

Sedimentary environment: It is thought that the transgression of the Izumi Group begun with this stage, because this formation consists predominately of fine to medium grained sandstone and intercalates layers of mudstone containing *Makiyama* (=*Sagarites*).

2. KUROSUNO FORMATION

This formation corresponds to the Kushigata Formation of Eguchi and Suzuki (1953), is almost the same as the Kokozura Formation of Iwai (1950) and Kamada (1962), and is correlated with the Yotsukura Formation of Hirayama (1952).

Type locality: Kurosuno, Izumi-cho, Iwaki City, Fukushima Prefecture. Thickness: 60 to 70 meters.

Lithology and stratigraphic relation: The Kurosuno Formation is distributed in the environs of Yotsukura, Yotsukura-cho and Izumida, Izumi-cho and in the Taga Area (Sugai and Matsui, 1957) south of the Yamada fault.

In the vicinity of Yotsukura the formation shows a gentle but complex fold structure and lies with clino-unconformity upon the Iwaki, Asagai and the Kunugidaira formations each which have a different geological structure. The basal conglomerate is of pebble size and comprises chert and sandstone derived from the Asagai Formation and muddy shale from the Shirasaka Formation. This formation consists mainly of grayish white massive siltstone with mica, pumice and *Makiyama* (=*Sagarites*), intercalated with layers of medium to coarse grained subarkose sandstone (0.5–3 meters) and soft rock conglomerate of mudstone, shale and pumice (0.5 meters in maximum thickness).

In the Taga Area, that is, in the vicinities of Kurosuno, Ueda and Yamada, this formation comes into contact with the Yunagaya Group by the Yamada fault in the northern part, with the Nakayama Formation in the western part and lies with clino-unconformity upon the Kameno-o Formation in the eastern part. The general strikes and dips are N30°E-N30°W and of 5°–20°E or W respectively. The structure is complex though gentle. This formation lies on the Nakosonoseki Formation with conformity and is superposed by the Quaternary Sodetamayama Formation with unconformity.

The Kurosuno Formation consists mainly of dark gray massive siltstone intercalated with thin layers (5–20 cm) of soft rock conglomerate, fine to coarse grained sandstone and pumiceous sandstone. The siltstone is diatomaceous and contains carbonaceous fragments, pumice, mica and *Makiyama* (=*Sagarites*). Molluscs, foraminifers and diatoms occurred from this formation.

The thickness of the formation exceeds 36 meters north of Kurosuno, 20 or more meters in the east of Ueda, 40 to 50 meters at Kokozura, Nakoso-cho and more than 50 meters in the north of Nagisa, Ueda-cho, averaging about 60 meters.

In the vicinity of Hiruno, Izumi-cho, the Kurosuno lies on the core of the Hiruno Anticline.

Sedimentary environment and geological age: This formation is composed predominately of siltstone which yielded molluscan species that lived in the neritic zone, thus it was deposited in the neritic zone.

The molluscan fossils indicate the Middle Miocene age of the Kokozura. *Turritella nipponica* Yokoyama, which is common in the Pliocene, occurred from the siltstone near Kurosuno. On the other hand, Saito (1963) pointed ont that the formation corresponds to a position ranging from the *Sphaeroidinella seminulina* zone to the *Globorotalia menardii*/*Globigerina nepenthes* zone and therefore may be Tortonian to Sarmatian in age.

3. SEKINOUE FORMATION

This formation nearly corresponds to the Hirono Formation of Sugai and Matsui (1957), and to the lower part of the Futaba-Tomioka Formation of Kamada (1962). It resembles the underlying Kurosuno Formation in lithofacies, but owing to their separated distribution their stratigraphic relation remains indistinct. Therefore, the Sekinoue Formation corresponds to the lower part of the so-called Taga Group distributed in the Tomioka Area (east of the Futaba thrust fault).

Type locality: Sekinoue, Hirono-cho, Futaba-gun, Fukushima Prefecture. Thickness: 164 meters.

Lithology and stratigraphic relation: This formation is distributed in the Tomioka Area (Sugai and Matsui, 1957), between Yusuji, Hirono-cho and Nakoya, Naraha-cho. The formation shows strikes of N-S to NNW-SSE and dips of 5° to 10°E. The Sekinoue Formation is in fault contact with the Yunagaya Group in the Tomioka Area, but rests on the Yunagaya Group with unconformity in the vicinities of Sekinoue and Nanamagari.

The Sekinoue consists mainly of dark olive, micaceous and pumiceous siltstone intercalated with thin layers of medium to coarse grained graywacke type sandstone and yields fossil molluscs, foraminifers, *Makiyama* and diatoms.

Sedimentary environment and geological age: From the lithology and molluscan fossils, it is considered that the formation was deposited in the neritic zone.

From the molluscan fossils, Kamada (1962) stated that the formation is Early Pliocene in age. The Pliocene age of this formation is also upheld by such foraminifers as, *Bulimina atriata* d'Orbigny, *Cibicides* sp., *Brizalina pseudobey richi* (Cushman), *Globigerina woodi* Jenkins and *Globigerina pachyderma* (Ehrenberg) (dextral).

YAMADAHAMA FORMATION (Fig. 9)

The Yamadahama Formation nearly corresponds to the Tomioka Formation of Sugai and Matsui (1957) and almost with the upper part of the Futaba-Tomioka Formation of Kamada (1962).

Type locality: Iwasawa, Naraha-cho, Futaba-gun, Fukushima Prefecture. Thickness: 40–50 meters.

Lithology and stratigraphic relation: This formation is distributed only in the Tomioka Area. It strikes NNW-SSE and dips at about 10°E and lies with unconformity upon the Sekinoue Formation.

The basal conglomerate (1–5 m thick) is composed predominantely of cobble to boulder size siltstone derived from the Sekinoue Formation. The lower part of the formation consists mainly of fine to coarse grained tuffaceous sandstone intercalated with thin layers of coarse grained arkose sandstone and coarse grained sandstone layers with abundant molluscan fossils in the lower part. The upper part comprises dark olive, micaceous, massive siltstone intercalated with thin layers of sandstone with pumice and carbonaceous fragments.

The unconformity between the Yamadahama and Sekinoue formations can be observed in the vicinities of Sekiyama and Iwasawa.

Sedimentary environment: Because this formation consists mainly of fine to coarse grained sandstone in the lower part and of siltstone in the upper part and yielded abundant fossils, it is thought that the lower part was deposited in the littoral zone and the middle to upper parts in a neritic environment.

SODETAMAYAMA FORMATION (Sugai and Matsui, 1957)

This formation represents the basal part of the Quaternary deposits. It is correlated with the Tatsuta Formation (Mita, 1951) distributed in the Tomioka Area.

Type locality: Sodetamayama, Yotsukura-cho, Iwaki City, Fukushima Prefecture. Thickness: More than 50 meters.

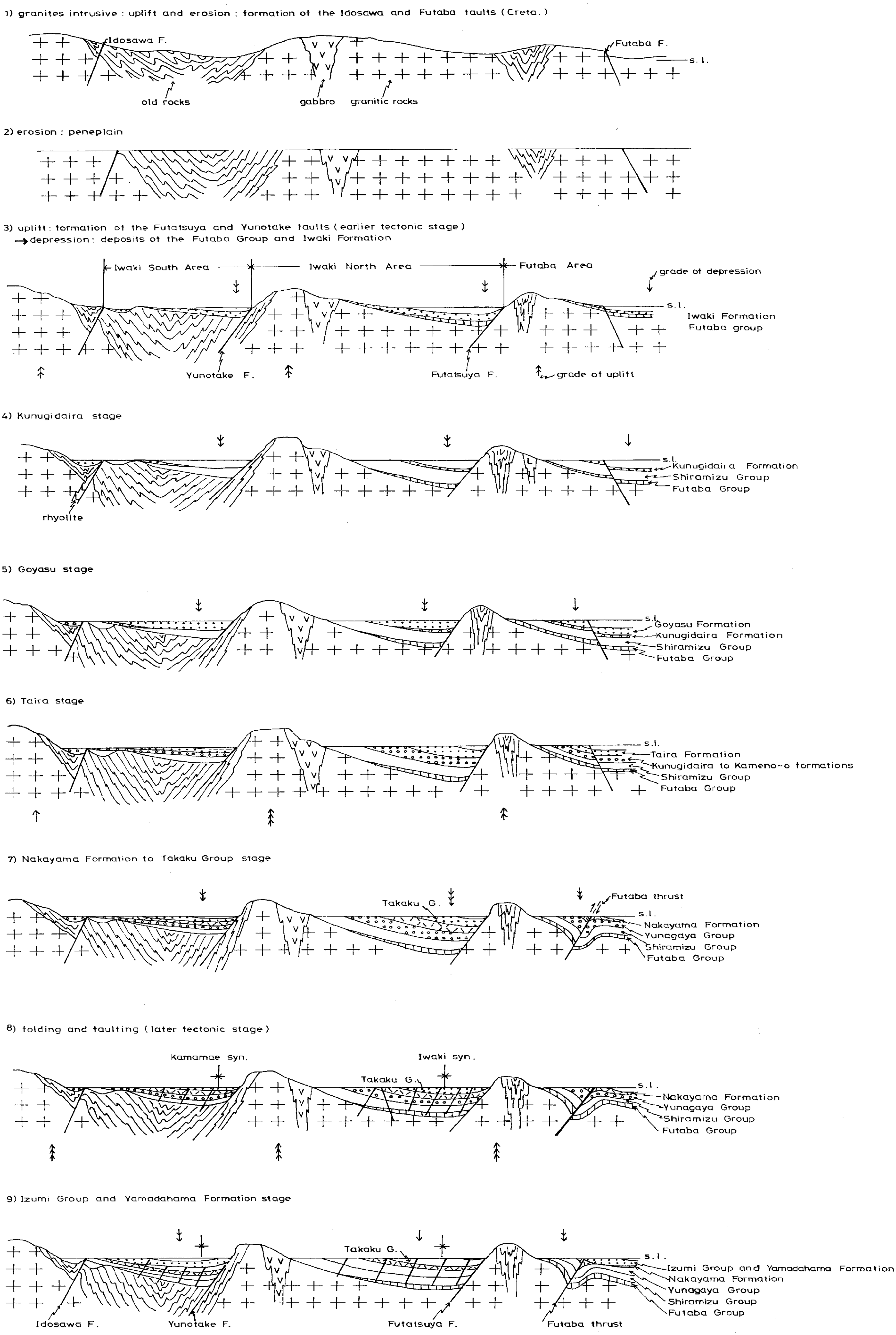


Fig. 10. Schematic map of the tectonic history of the Joban coal-field

Lithology and stratigraphic relation: This formation is distributed in the environs of Sodetamayama, Yotsukura-cho and Kanayama, Ueda-cho and rests on the Futaba, Shiramizu and Izumi groups with angular unconformity. It is composed predominately of yellowish brown, medium to coarse grained sandstone showing good development of cross-bedding.

III. TECTONIC HISTORY (Fig. 10)

After the development of the pre-Permian to Permian rocks of the Gozaisho, Yaguki and Takakurayama series in the investigated area, there occurred intense tectonic movements associated with uplift and the intrusion of the older and younger granitic rocks and the ultrabasic to basic rocks, by which metamorphism, folding, faulting and block movements took place. This orogeny was followed by deep erosion over a long time, and the old Abukuma Mountains after peneplanation was subjected to gradual subsidence of the land and marine transgression of the Late Cretaceous seas in the Futaba and Iwaki North Areas. And the sediments of the Futaba Group were deposited. The Cretaceous seas advanced over the peneplained land surface although rejuvenation had already commenced in the hinterland. After deposition of the Futaba Group there occurred uplift of the area associated with the first movement of the Futatsuya and Yunotake faults. These major faults were responsible for subdividing the area into three sedimentary basins represented by the Futaba Area, the Iwaki North Area and the Iwaki South Area (the earlier tectonic movement).

After a short period (post-Cretaceous to Eocene) of subaerial denudation followed with gradual but different subsidence of the area, there occurred marine transgression and deposition of the sedimentary rocks of the Shiramizu Group. During and also possibly even before deposition of the Shiramizu Group the three areas mentioned above were subjected to different subsidence rates, and this may have been one of the reasons of the different development and distribution of the Iwaki Formation, the lowest of the Shiramizu Group. The lithofacies and thickness variation of the different formations of the group strongly suggests that the Iwaki North and Iwaki South Areas subsided more than the Futaba Area, and this is inferred to have had intimate relation with the different movements of the respective blocks which were bounded by the Futatsuya and Yunotake faults. Deposition in the three sedimentary basins was interrupted owing to regression of the shallow sea and to the filling by volcanism during the accompanying uplift of the Shiramizu Group. This was followed by a short period of subaerial denudation by which the land was leveled. It is upon this land that the second marine transgression commenced from the east. This marine invasion took place almost parallel with the different subsidence movements of the three sedimentary basins. The different subsiding movements of the respective basins is indicated by the development and distribution of the Kunugidaira Formation, in the three sedimentation areas. This different subsiding movements of the respective basins is also shown by the lithology, as, terrestrial conglomerate and tuff were deposited in the Futaba Area, whereas littoral and brackish sandstone and mudstone were deposited in the Iwaki North and Iwaki South areas during development of the upper part of the Kunugidaira Formation. There was acidic volcanic activity during deposition of the Kunugidaira Formation, especially during deposition of its lower to middle parts.

In both the Iwaki North and Iwaki South areas marine transgression continued throughout Goyasu time associated with local upheaval as shown by that the Goyasu lies with unconformity upon the Shiramizu group beyond the depositional field of the Kunugidaira Formation in the Iwaki North Area. In the Iwaki South Area the Goyasu Formation lies on the Kunugidaira with partial unconformity and its distribution extends to the environs of Iri-Tono, where the Goyasu covers the basement rocks with unconformity, showing significant overlap.

The physical conditions were somewhat different during deposition of the Kunugidaira and Goyasu formations in the Iwaki North and Iwaki South areas. From the thickness in lithofacies and distribution of the stratal units in each area, it seems evident that the center of the sedimentary basin migrated in northwest direction, as is indicated by the overlapping of the Goyasu upon older formations in that direction. After the deposition of the Goyasu Formation, marine transgression gradually advanced to flood the three areas and attained the maximum during Kameno-o time. After deposition of the Kameno-o Formation marine regression commenced in each of the sedimentary basins accompanied in part by submarine eruption of andesitic to basaltic tuff breccia.

The Misawa Sandstone Member which has a lithofacies typical of a regressive phase was deposited thickly in the Iwaki North aad Futaba areas. Accompanying the regression of the Yunagaya Group which continued to Nakayama time there was uplift of the Abukuma Mountains. This uplift was largest in the Futaba Area, next in magnitude in the Iwaki North Area and smallest in the Iwaki South Area. During Nakayama time subsidence increased in the order from the Futaba Area, the Iwaki North Area to the Iwaki South Area. Namely, the Nakayama Formation in the Futaba Area consists only of basal conglomerate of andesitic to basaltic tuff breccia and lies with unconformity upon the Misawa Sandstone Member. Whereas, the formation in the Iwaki North Area lies on the Misawa Sandstone Member with a partial unconformity. And, in the Iwaki South Area the formation overlaps successively the Honya Mudstone Member, the Kameno-o Formation, the Mizunoya Formation and the Goyasu Formation in the order mentioned from the southeast to the northwest.

The sedimentary rocks of the Takaku Group were deposited in both the Iwaki North and Iwaki South areas, but not in the Futaba Area which had already become land.

The Futaba Flexual Belt or the Futaba thrust faults in the Futaba Area were formed during the time from deposition of the Nakayama Formation to that of the Takaku Group. After deposition of the Takaku Group, the investigated area was subjected to uplift accompanied by folding and faulting (the later tectonic movement). The main faults developed at this time are the Shirasaka, Akai, Harakida and Tabasaka faults, etc., and the outstanding fold structures are the Iwaki and Kamamae synclines, the Hiruno anticline and the Futaba fold. After a period of continued erosion, subsidence again occurred mainly in the Futaba Area and in the area between Izumi-cho and Ueda-cho, and the rocks of the Izumi Group and of the Yamadahama Formation were deposited in this sedimentary basin. The uplift occurred before and after the deposition of the Yamadahama Formation. And these movements resulted in the construction of the Yamada fault and the gentle fold structures observed in the Izumi Group and the reactivity of the Futaba thrust faults. And, at this time the present area was separated into five blocks, namely, the Iwaki North Block, the Iwaki South Block, the Futaba Block, the Tomioka Block and the Taga Block as already pointed out by Sugai and Matsui (1957). After the repetition of emergence and submergence movements, the Pleistocene and Holocene sediments were deposited, and the prevailing conditions became modified to Recent.

GEOLOGICAL STRUCTURE

I. FOLDS

In the area studied, the major fold structures (refer to annexed maps) are known as the Iwaki syncline and Hiruno anticline in the Iwaki North Area, the Kamamae syncline in

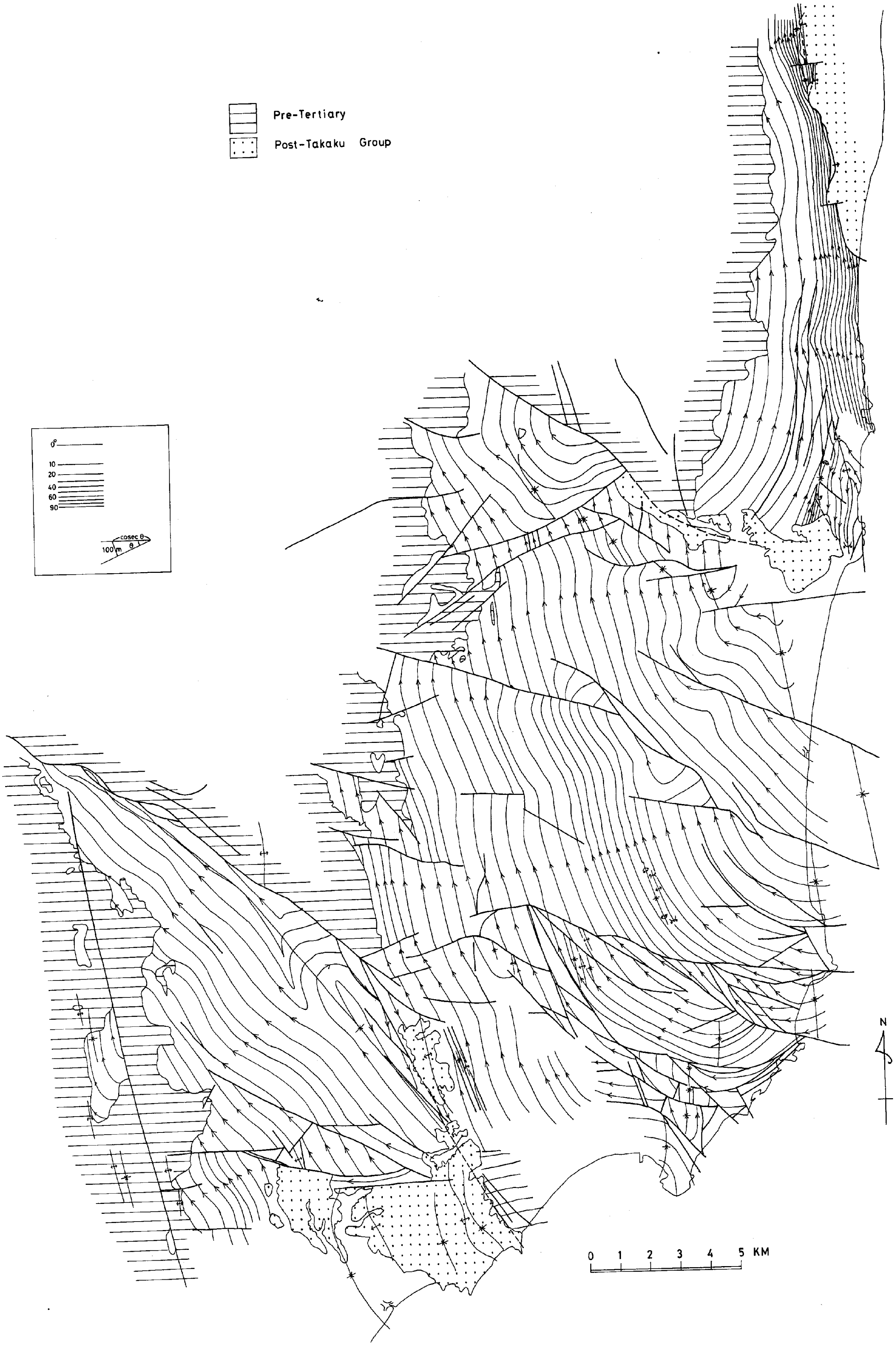


Fig. 11. Strike contour map

the Iwaki South Area and the Futaba fold structure in the Futaba Area. Most of these geological structures are post-Takaku Group or pre-Izumi in age. The smaller geological structures are developed in the vicinities of Yotsukura, Yoshinoya and Misawa.

The Iwaki syncline with general trend of N-S to NNW-SSE plunges northwards and is the major synclinal structure in the Iwaki North Area. All of the formations distributed in the Iwaki North Area join in development of the western wing of the Iwaki syncline. The strata from the Shiramizu Group to the Takaku Group were deposited successively in upward sequence towards the center of the syncline. The axis of the syncline extends into the Pacific Ocean in the vicinity of the mouth of the Natsui River. The axis is displaced step-like regularly towards the west by the Akanuma fault, the Nagi fault and the Niitagawa fault in the area north of the mouth of the Natsui River and by the Natsuigawa fault, the Shirasaka fault and the Ena fault in the southern part of the same river. The apparent horizontal displacement ranges from 1.5 to 6.3 kilometers (Fig. 11). The Iwaki synclinal structure is subdivided into three parts by the Shirasaka and Akai faults (Sugai and Matsui, 1957). Namely, the syncline plunges northwards with general trend of N-S in the southern part, south of the Shirasaka fault and in the middle or between the Shirasaka and Akai faults, and with trends of NNW-SSE to NW-SE in the northern part, north of the Akai fault.

From the analysis of the stress field in the Iwaki North Area, most of δ_3, the axis of the maximum compressive principal stress, lies with high angle (50°–85°) to the horizontal plane.

The Hiruno Anticline (Ishiguri, 1968 MS) which is situated between the Iwaki syncline and the Kamamae syncline in the Iwaki South Area lies east of the Tabasaka fault and its axis trends NNW-SSE. The Goyasu Formation constitutes the core of the anticline. The west wing of this anticline was cut by the Tabasaka and Watanabe faults and a part of the east wing by the Fujiwara fault. According to the analysis of the stress fields in the environs of this anticline, σ_3 shows high angle up to nearly vertical.

The Kamamae syncline (Ishiguri, 1968 MS), corresponds to the Kadono basin structure of Sugai and Matsui (1957); it is an almost complete basin structure (plunging southwards) with axis trend of N40°–60°W. It is thought that the syncline was originally continuous with the west wing of the Hiruno anticline, whereas the east wing was cut by the Tabasaka fault. The stress field δ_3 in the Iwaki South Area lies with high angle up

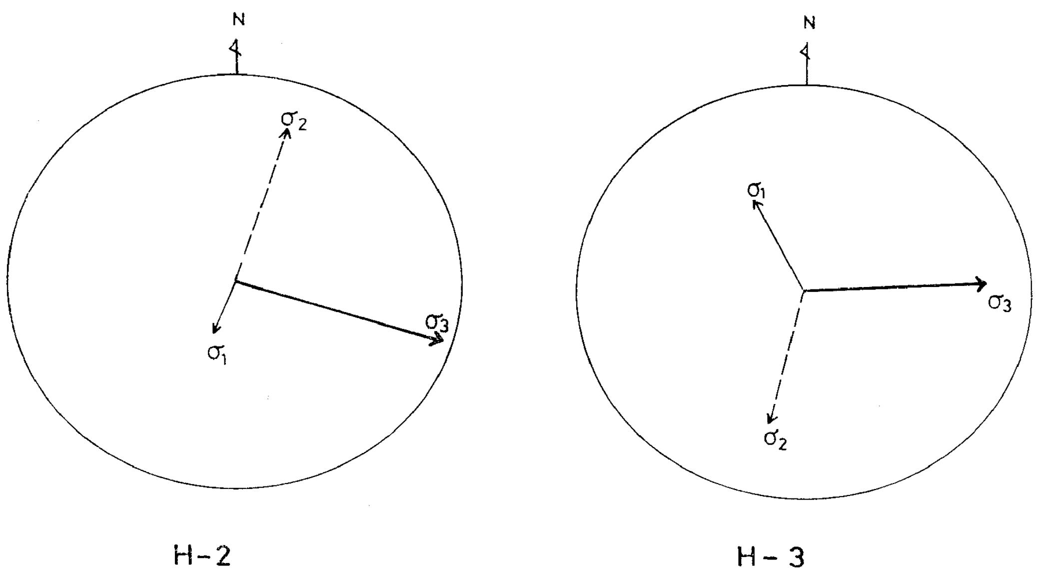


Fig. 12. **Principal stress field along the Futaba thrust fault**

to nearly vertical to the horizontal plane.

The Futaba fold structure with N10°–20°W strike extends northwards from Yusuji to north of the Iriumi spa and consists mainly of one syncline and one anticline, which show isoclinal folding with west dip.

Field observations suggest that the Futaba fold structure was formed under the stress field where σ_3 lies nearly in east or west direction with horizontal angle (Fig. 12). When the dips of each formation west of the Futaba thrust are observed, the Futaba Group and the Iwaki Formation dips at 10°–15°E, the Asagai and Shirasaka formations at 20°–40°E, and the Yunagaya Group and the Nakayama Formation show dips of 50°–80°E or W. Whereas, in the east of the Futaba thrust, the Izumi Group dips at about 10°E, and this as already reported by Ninagawa (1954) shows that the formations older than the Izumi Group were not folded and dip eastwards gently. Hence, this fold structure was originally a flexual fold which subsequently transformed into the present structure by the horizontal stress of the tectonic movement (before the deposition of the Izumi Group).

II. FAULTS

There are many faults in the investigated area as shown in Fig. 14 and they are featurized as follows, 1) most of the faults except the Futaba thrust and Yamada fault are covered by the sedimentary rocks of the Izumi Group; 2) all except the Futaba thrust and Shobusaku thrust are normal faults; 3) the main faults observed in the field are normal faults with the strikes of NW-SE, through E-W, to ENE-WSW and with dips towards the south, southwest or west (Table 2). The observed minor faults are normal faults with the trends dominantly of NW-SE, E-W or ENE-WSW like the main faults (Fig. 13). Besides, as already pointed out by Hoshino (1965) the minor faults observed in the coal-mines have the same tendencies as the major ones; 4) most of the faults can be classified into sets (Table 5) denoted the Harakida, Shirasaka, Karasudate, Idosawa, Tabasaka and Yumoto fault sets by the strike of the fault plane, and the faults which belong to the Harakida, Shirasaka and Tabasaka fault sets are dominant. Most of the faults are normal and show dip-slip; 5) most of the faults, except the Futaba and Yamada faults, which cut the Tertiary sedimentary rocks were formed by tectonic movements of post-Takaku Group and pre-Izumi Group time (the later tectonic movement).

EXPLANATION OF THE MAIN FAULTS (Fig. 14, Table 2)

Futaba Thrust Fault; This thrust fault is responsible for the major geologic structure forming the boundary between the Futaba and Tomioka areas. This thrust extends with N-S to NNW-SSE trend along the western margin of distribution of the Izumi Group from Yusuji, Hirono-cho to the vicinity of Iwanuma-cho, Miyagi Prefecture and is the same as the "Hisanohama-Iwanuma dislocation line" of Yabe and Aoki (1924). It is considered that the thrust was formed before deposition of the Izumi Group but again reacted after development of the Izumi Group. The movement of the reactive fault is considered to have been slight from the following reasons, that is, 1) the shear along this thrust is small, 2) the pumice grains contained in the Izumi Group adjacent to the thrust are little deformed and 3) the thrust is discontinuous (Tsuneishi, 1966). The fault is observed at the west of Yusuji, the west of Tsukiji, the west of Shimo-Kitazawa and in the environs of the Iriumi spa. The displacement by the fault is estimated to be about 200 meters.

Futatsuya Fault; This major fault separates the Futaba Area from the Iwaki North Area and also controlled the geological structures of the present area. The general strike and dips are N60°–80°W and 55°–65°S respectively. The pre-Tertiary rocks on the

Fig. 13. Minor fault pattern in the Joban coal-field

Table 2. Characteristics of the main faults

Area	Fault Name	Class.	Strike	Dip	Vert. Displ. (m)	Remarks
Futaba Area	Futaba F.	reverse	NNW-SSE	35-70 W	200 ±	be cut & covered by Izumi group
	Shinyashiki F.	normal	N5E	70 W	10 ±	
	Syobusaku F.	reverse	N10-40E	70 E	30 ±	
	Futatsuya F.	normal	N60-80 W	55-65S	550 ±?	
Iwaki North Area	Niitagawa F.	normal	E-W-N80W	60 S	350 ±	large displacement toward E
	Mizushina F.	normal	E-W-N80E	?	?	depress toward S
	Nagi F.	normal	N70E	55 S	350 ±	large displacement toward E
	Okura F.	normal	N60-70E	60 N or S	?	
	Nakadaira F.	normal	N60-70E	?	?	
	Hirakubo F.	normal	N45W	45-50 SW	220 ±	small displacement toward SE
	Omuro F.	normal	N35W	60-70 SW	160 ±	large displacement toward SE
	Akai F.	normal	N60-70W	60 S	380 ±	
	Yamazaki F.	normal	N30-70W	50 SW	150 ±	an extension part of Omuro fault
	Tatsusawa F.	normal	N80W	65 S	200±	small displacement toward W
	Numanouchi F.	normal	N60W	50 S	120 ±	
	Shimizu F.	normal	N60W	70 S	150 ±	
	Shirasaka F.	normal	N80E-N60W	60-70 S	430 ±	
	Komoda F.	normal	N60W	?	250 ±	depress toward S
	Karasudate F.	normal	N75E-E-W-N60W	70 S	380 ±	
	Iwaki F.	normal	N70E	?	?	
	Aikawa F.	normal	N40W	50-70 S	290 +	
	Sumiyoshi F.	normal	N10W	40 E	10 ±	
	Iwaide F.	normal	N20W	74 E	30 ±	
	Kuramochi F.	normal	N40-70W	55 S?	10 ±	depress toward S
	Noda F.	normal	E-W	70 S	120	
	Harakida F.	normal	N50W-E-W	50-70 S	150 ±	
	Ena F.	normal	N60W-E-W-N70E	50 S	160 ±	north dip at Kamikajiro
	Fujiwara F.	normal	N30-70W	65 SW	200 ±	
Iwaki South Area	Yunotake F.	normal	N60W	45-80 SW	250 -	
	Tabasaka F.	normal	N20-50W	60 S	250 ±	
	Watanabe F.	normal	N40W	?	?	
	Osawa F.	normal	N60W	63 S	?	small displacement
	Ebata F.	normal	N60-70W	60-70 W	10 ±	
	Yamada F.	normal	N70W-E-W-N80E	60-80 S	400 ±	cut the Izumi Group
	Amakida F.	normal	E-W-N80W	65-85 S	250 ±	an extension part of Yamada fault
	Idosawa F.	normal	N10W	60-80 W	400 ±	

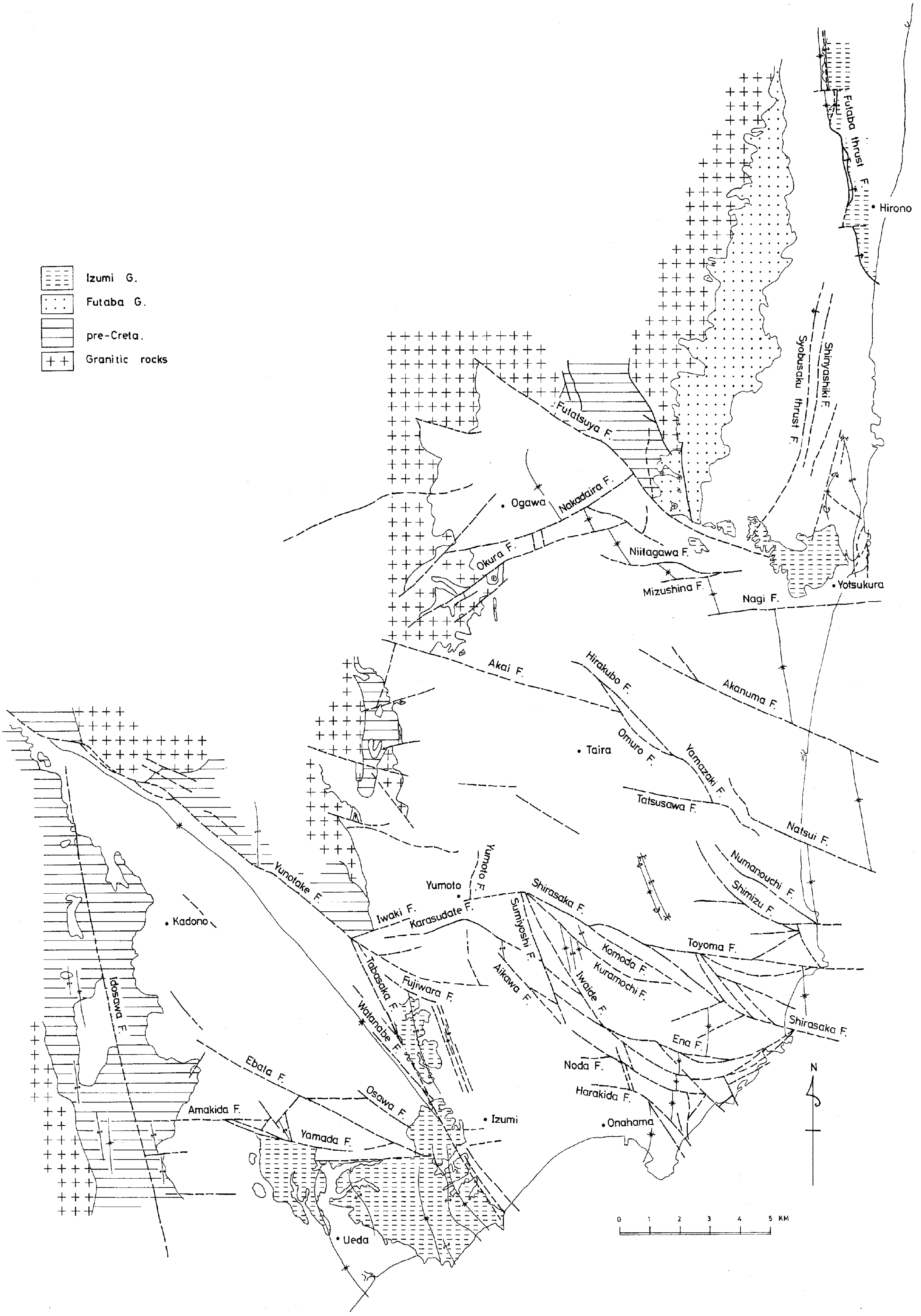


Fig. 14. Main fault pattern in the Joban coal-field

north side of the fault come into contact with the Tertiary sediments on the south side. The Cretaceous sedimentary rocks (400 meters thick) distributed in the north of this fault are not observed at the surface at the south side. The fault plane is observed in the vicinity of Yaguki, Yotsukura-cho, etc., where the sandy shale of the pre-Tertiary (north side) is separated from the conglomerate-bearing coarse grained arkose sandstone of the Goyasu Formation (south side) by the fault which has N40°W strike and dip of 67°S and a shear zone of about 10 meters in width. It is difficult to determine the vertical displacement of the fault, but it is considered to be about 550 meters. The displacement decreases towards the southeast. This fault is a normal one showing dip-slip and is covered by the Kurosuno and Sodetamayama formations. Field evidence points to that the fault was formed prior to the deposition of the Iwaki Formation and that it had continued to act intermittently from the time of the Iwaki up to the Takaku Group.

Akai Fault; This fault trends N60°–70°W and can be traced for about 6.2 kilometers from the southern foot of Mt. Akai-dake to Jumonji. The fault plane is observed at the south and southwest of Joju, where the general strike and dip are N70°W and 60°S respectively. This fault is a normal one with about 380 meters in vertical displacement and separates the Iwaki Formation from the granitic rocks southeast of Joju and from the Goyasu Formation in the vicinity of the Akai Middle School.

Shirasaka Fault; This fault is a remarkable major one that cuts the Tertiary sedimentary rocks in the Iwaki North Area. This fault extends with N80°E to E-W trend and can be traced for about 12 kilometers from Yumoto via the Iwaki coal mining station to the vicinity of Kaishun-en, Taira-Toyoma where the strike becomes N60°–70°W. The fault can be traced for about 12 kilometers. The fault plane trending N80°E to E-W is not observed at the surface, but has been ascertained underground in the coal-mines. The fault plane of N60°–70°W strike can be observed at many places. For instance, the Goyasu Formation is separated from the Misawa Sandstone Member by a fault with N60°W strike and 70°S dip in the environs of the abandoned Kashima Shaft and from the Nakayama Formation by a fault with N63°W strike and dip of 65°S at Okushidasaku. The Mizunoya Formation contacts with the Nakayama Formation by the fault with N50°W strike and 60°S dip at Taira-Matsukusune and, besides, the Kameno-o Formation is separated from the Honya Mudstone Member by the fault with N50°W strike and 65°S dip at Shimo-yata, Kashima-cho. The displacement by the fault seems to be about 200 meters in average, but attains a maximum displacement of about 430 meters at Taira-Matsukusune and Kami-Kuramochi, Kashima-cho.

Karasudate Fault; This fault extends in ENE, E and SE directions from the north of Joban-Fujiwara to the south of Kameno-o, Joban-Mizunoya and joins the Sumiyoshi fault at the south of Kameno-o; the displacement gradually decreases southwards. The extension of the fault as observed in the field is about 5 kilometers. The fault plane is seen in the vicinities of Joban-Yumoto and Joban-Mizunoya. At the former place the Iwaki Formation is separated from the Kamiyata Sandstone Member by a fault which trends N85°W and dips of 72°S, and at the latter the Goyasu and Mizunoya formations and/or only the latter formation are cut by the fault that trends N70°W and dips 40°S. The fault is a normal one with dip-slip and down throw towards the south; its displacement attains about 380 meters.

Harakida Fault; This fault, with a displacement of about 150 meters, extends in E-W direction in the environs of Onahama-Harakida, changes to N50°W and extends towards Onahama-Shimo-Kajiro. The fault is a normal one, traced for about 3.7 kilometers and shows dip-slip. The fault plane is observed at Onahama-Harakida and Onahama-Mizuoshi. The fault plane strikes E-W and dips at 70°S at the former locality and N50°W and 50°–65°S at the latter.

Yunotake Fault; This major fault separates the pre-Tertiary rocks from the Tertiary sediments and forms the boundary between the Iwaki North Area and the Iwaki South Area. Like the Futatsuya fault it controls the geological structure of the investigated area. The fault was formed before deposition of the Iwaki Formation but also had influence up to the Takaku Group. The fault with dip of 60°S extends E-W to N60°W along the steep slope south of Mt. Yunotake and is a normal one traceable for about 12 kilometers and with a displacement of about 250 meters.

Tabasaka Fault; This fault is associated with the Yunotake fault and is a normal one trending N20°–50°W and dips at 60°W. The fault is covered by the Izumi Group in the east of Hiruno, Izumi-cho and separates the Kamamae syncline from the Hiruno anticline. It is thought that the fault extended to Otsurugi, Izumi-cho and cut the Kameno-o Formation, but decreased in displacement. This fault is displaced by the Watanabe fault.

Yamada Fault: This fault is a major one and separates the Iwaki South Area from the Taga Area. It is a normal fault and extends for about 5 kilometers from Kami-Yamada, Yamada-cho to Jukindaira, Izumi-cho. The strike and dip are N70°W, E-W or N80°E and dips of 60°–80°S and the displacement is about 400 meters. This fault cuts the sediments of the Izumi Group like the Futaba thrust fault and, thus, seems to have been formed after deposition of the Izumi Group.

Idosawa Fault; This fault with 200–400 meters displacement extends from Iri-Tono to Nakoso-cho for about 15 kilometers with N10°W strike and dips of 60°–80°W. This fault cut the basement rocks and the Kunugidaira Formation in the Kuroda basin and the Goyasu Formation at Ochiai, Iri-Tono. It is presumed that the fault was formed before deposition of the Tertiary rocks but reacted after deposition of the Goyasu Formation. This is a major fault and it much controlled the development of the Abukuma Mountain like the Futaba flexual belt and the Tanakura shear belt.

FAULTS IN EACH AREA

In the foregoing paragraph an outline of the main faults distributed in the area investigated was given, and in this section the development of both major and minor faults in each area will be described to know their tendency in the area. Here, the term major faults is used to denote the faults that can be expressed individually on the geological map of the scale of 1/50,000, and the minor faults the fractures which are too small to be indicated on the geological map of the same scale.

1. FUTABA AREA

In the Futaba Area (Table 2) the most remarkable major fault is the Futaba thrust fault which forms the boundary between the Futaba and Tomioka areas and the eastern margin of the Abukuma Mountains. There are also other major faults in this area, for example, the Shinyashiki normal fault and the Shobusaku thrust fault both of NNE-SSW strike. The faults of smaller scale show NNW-SSE and E-W trends in the vicinity of Kanagasawa and those with WNW-ESE, N-S and NNE-SSW trends in the environs of Tanoami. The faults east of Nanamagari and in the vicinity of Hirono trend about E-W. These faults of small scale cut the Futaba thrust fault, thus they may have developed at the time of the major faults in this area.

There are also found minor reverse faults which strike parallel to the Futaba thrust and minor normal faults with E-W strike, the latter cut the minor reverse faults in the area along the Futaba thrust fault. In the area from Hisanohama to Shinyashiki there are minor faults showing trends parallel to the Shinyashiki and Shobusaku faults. Close to the

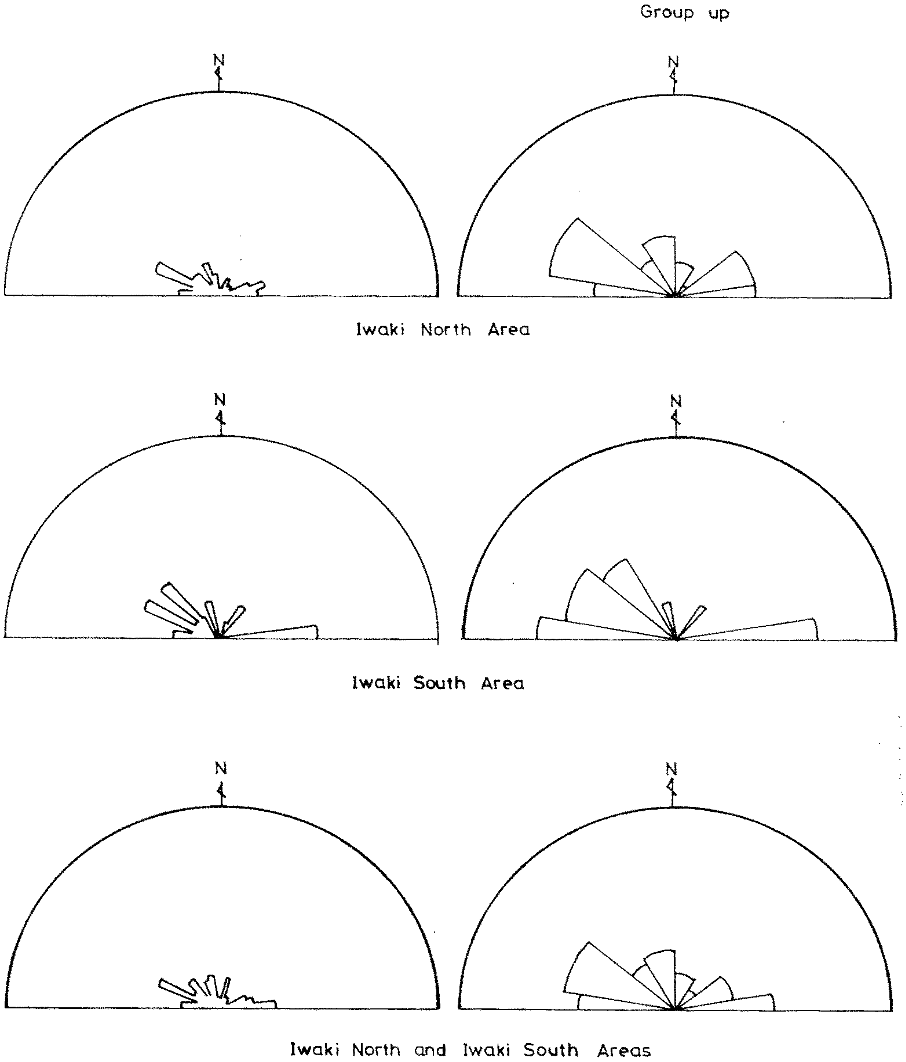


Fig. 15. Strike frequency curve of major faults

Table 3. Number and percentage of the major faults which belong to the individual fault sets in each area

Fault Set	Iwaki North Area		Iwaki South Area		Whole Area	
	Nos.	%	Nos.	%	Nos.	%
Harakida fault set	15	18.0	7	31.5	25	21.2
Shirasaka fault set	24	28.8	6	27.0	31	26.3
Karasudate fault set	15	18.0	0	0	15	12.7
Idosawa fault set	12	14.4	2	9.0	16	13.5
Tabasaka fault set	9	10.8	5	22.5	15	12.7
Yumoto fault set	7	8.4	0	0	11	9.2
NE-SW	2	2.4	2	9.0	5	4.2
total	84	100.6	22	99.0	11	99.8

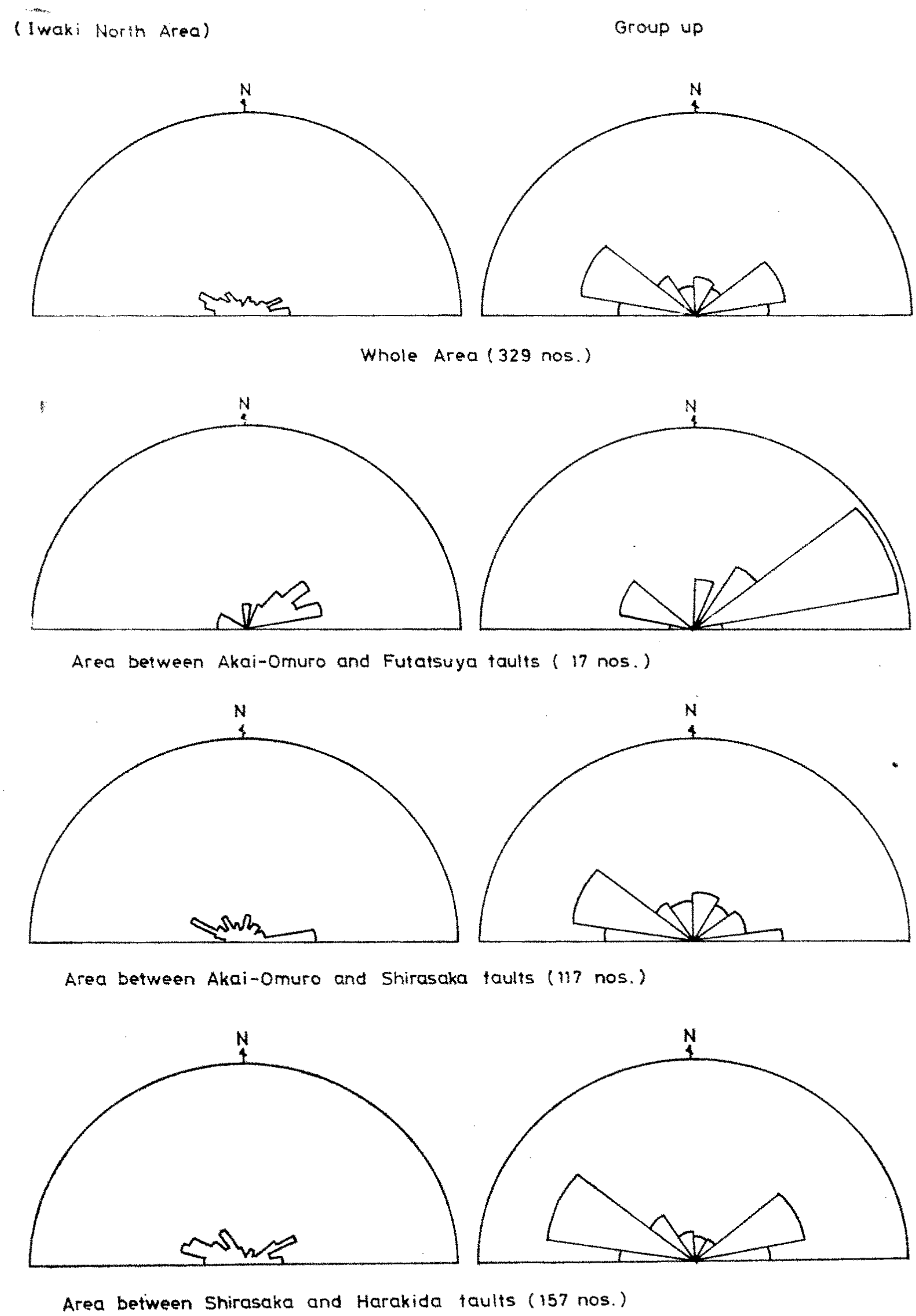


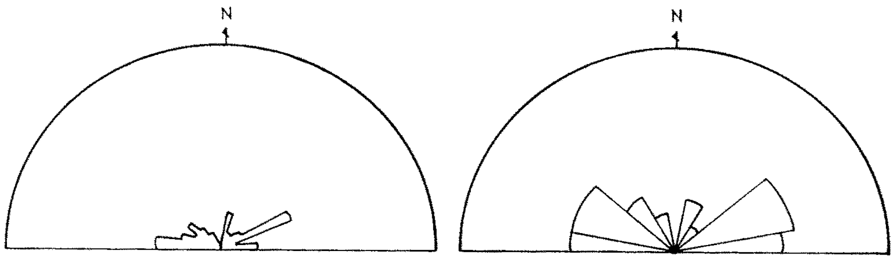
Fig. 16. Strike frequency curve of minor faults

Futatsuya fault, there are minor faults with trends of WNW-ESE, E-W and WSW-ENE. These faults make conjugate sets, and the minor ones parallel to the major faults were formed at the same time as their subordinate ones.

2. IWAKI NORTH AREA

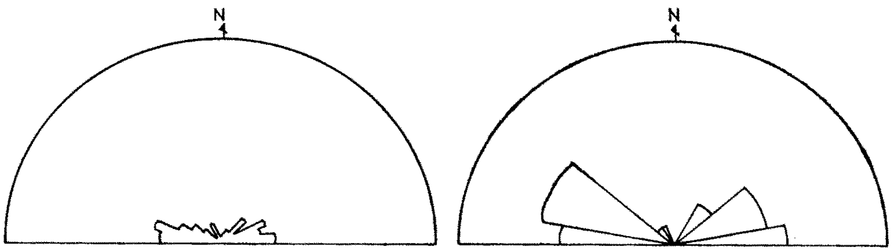
In this area the major faults (Table 2) have trends of E-W, WNW-ESE and NNW-SSE and, especially, the former fault trends are most dominant. The faults with WNW-ESE strike are presented by the Futatsuya, Yunotake, Shirasaka, Shimizu, Numanouchi and

Group up



Area between Aikawa-Harakida and Yunotake-Tabasaka faults (38 nos.)

(Iwaki South Area) (65 nos.)



(Iwaki North and Iwaki South Areas) (394 nos.)

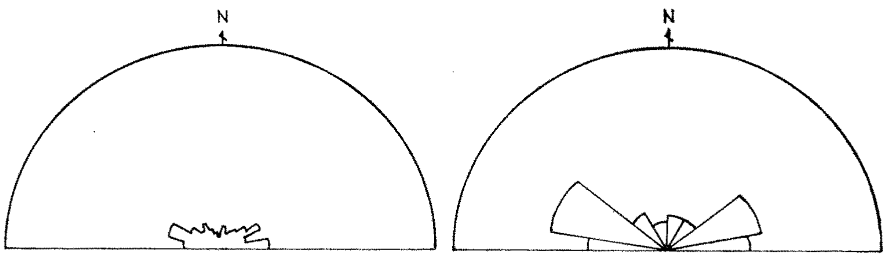


Fig. 16–continued

Table 4. Number and percentage of the minor faults which belong to the individual fault sets in each area

Fault set	Iwaki North Area		Iwaki South Area		Iwaki Both Areas	
	Nos.	%	Nos.	%	Nos.	%
E-W set	57	17.1	17	25.5	74	1 .0
WNW-ESE set	88	26.4	20	30.0	108	27.4
NW-SE set	36	10.8	3	4.5	39	9.9
N-S-NNW-SSE set	24	7.2	3	4.5	27	6.8
N-S-NNE-SSW set	29	8.6	1	1.5	30	7.6
NE-SW set	26	7.8	7	10.5	33	8.4
ENE-WSW set	69	20.7	14	21.0	83	21.2
total	329	98.6	65	97.5	394	99.9

Harakida faults. The faults with E-W strike are represented by the Shirasaka, Harakida and Tatsusawa faults. Also, the faults of NNW-SSE trend include the Sumiyoshi and Iwaide faults. The secondary prominent faults strike NW-SE and include the Hirakubo, Yamazaki and Aikawa faults. The faults with N-S to N30°E and NE-SW strike amount to less than 10 percent of the whole (Fig. 15, Table 3).

Because the faults with strikes of WNW-ESE and NNW-SSE are parallel to the Futatsuya, Yunotake and Idosawa faults which strongly controlled the lithology and distribution of the Tertiary formations, it is thought that the latter are old faults and the former the associated ones. In the Onahama area, many of the faults with E-W and ENE-WSW strike are actually a continuation of the faults of WNW-ESE trend. Thus, it seems that the three were originally the same fault.

On the contrary, the minor faults with WNW-ESE, ENE-WSW and E-W trend are dominant in this area and occupy 65 percent of the whole. The next prominent faults are those with NW-SE strike. The less prominent faults are those with N-S to N30°W, N-S to N30°E and NE-SW strike and amount to less than 10 percent. However, the tendency is more or less different in each area (Fig. 16, Table 4).

It is recognized that the three minor faults groups of WNW-ESE, E-W, and ENE-WSW cross one another, which shows that they were formed penecontemporaneously.

Among the major and minor faults in the area those with WNW-ESE strike are more dominant than those with NNW-SSE strike. Thus, it is considered that the faults in this area had been strongly influenced by the old faults of WNW-ESE strike.

3. IWAKI SOUTH AREA

The most prominent major faults in this area (Table 2) are the ones with E-W strike (Amakida and Yamada faults), those with WNW-ESE strike are represented by the Yamada, Ebata and Osawa faults and the ones with NW-SE strike include the Tabasaka and Watanabe faults. The prominent faults of second rank (Table 3, 4) are those with NNW-SSE trend and include the Idosawa fault and others with NE-SW strike; these amount to 10 percent of the total. The faults with NW-SE strike show characters near to the ones with NNW-SSE trend. Thus, most of the faults belong to the three groups of WNW-ESE, E-W and NNW-SSE, and from the consideration that the former two groups have the same system in origin, the tectonic movement, which formed the old faults of NNW-SSE and WNW-ESE trends, influenced the Tertiary System. It is thought that the faults cutting the Tertiary sediments developed under the strong influence of the faults showing the latter trend.

Most of the dominant minor faults trend E-W, WNW-ESE and ENE-WSW, cross one another and make conjugate sets. The three fault groups occupy about 76 percent of the total faults. On the other hand, the minor faults with NNW-SSE and NW-SE trends nearly parallel to the Idosawa fault amount to less than 10 percent of the total.

FAULT SET

As described in the foregoing paragraph, most of the major faults can be classified into six fault sets (Table 5), their trends are grouped into, E-W, WNW-ESE, ENE-WSW, N-S to NNW-SSE, NW-SE and N-S to NNE-SSW sets. The faults are classified according to their trend into the following fault sets, namely, Harakida, Shirasaka, Karasudate, Idosawa, Tabasaka and the Yumoto fault sets. The names of these fault sets are used following the proposal of Hoshino (1965) with some modification (Figs. 17–18, Table 5).

The strike and dip of the fault(s) of each set, the name of the faults included into each set and the nature of them is given in Table 5.

Table 5. Characteristics of individual fault sets

FAULT SET	STRIKE	DIP	MAIN FAULTS	NATURES
Harakida	N80E-N80W	50-80 S	Shirasaka, Harakida, Ena, Noda, Amakida, Yamada, Tatsusawa	normal dip-slip fault : max. v. d. is 250 m.
Shirasaka	N50-N80W	50-80 S	Futatsuya, Yunotake, Akai, Shirasaka, Harakida, Komoda, Shimizu, Ebata, Numanouchi, Yamada, Yamazaki, Osawa	normal dip-slip fault : max. v. d. is 430 m.
Karasudate	N50-80 E	50-70 S or N	Karasudate, Iwaki, Ena, Nakadaira, Okura	normal dip-slip fault : max. v. d. is 380 m. : Occurring at right angle to Idosawa fault set.
Idosawa	N5-30W	40-90 E or W	Idosawa, Sumiyoshi, Iwaide, Futaba, Tabasaka	normal dip-slip or strike-slip fault, except Futaba reverse fault.
Tabasaka	N30-50 W	40-70 SW	Tabasaka, Aikawa, Omuro, Watanabe, Kuramochi, Hirakubo, Yamazaki	dip- or strike-slip fault : max. v. d. is 290 m.
Yumoto	N5-30 E	50-70 E or W	Yumoto, Shinyashiki, Syobusaku	small displacement : Occurring at right angle to Harakida and Shirasaka fault set.

max. v. d. : maximum vertical displacement

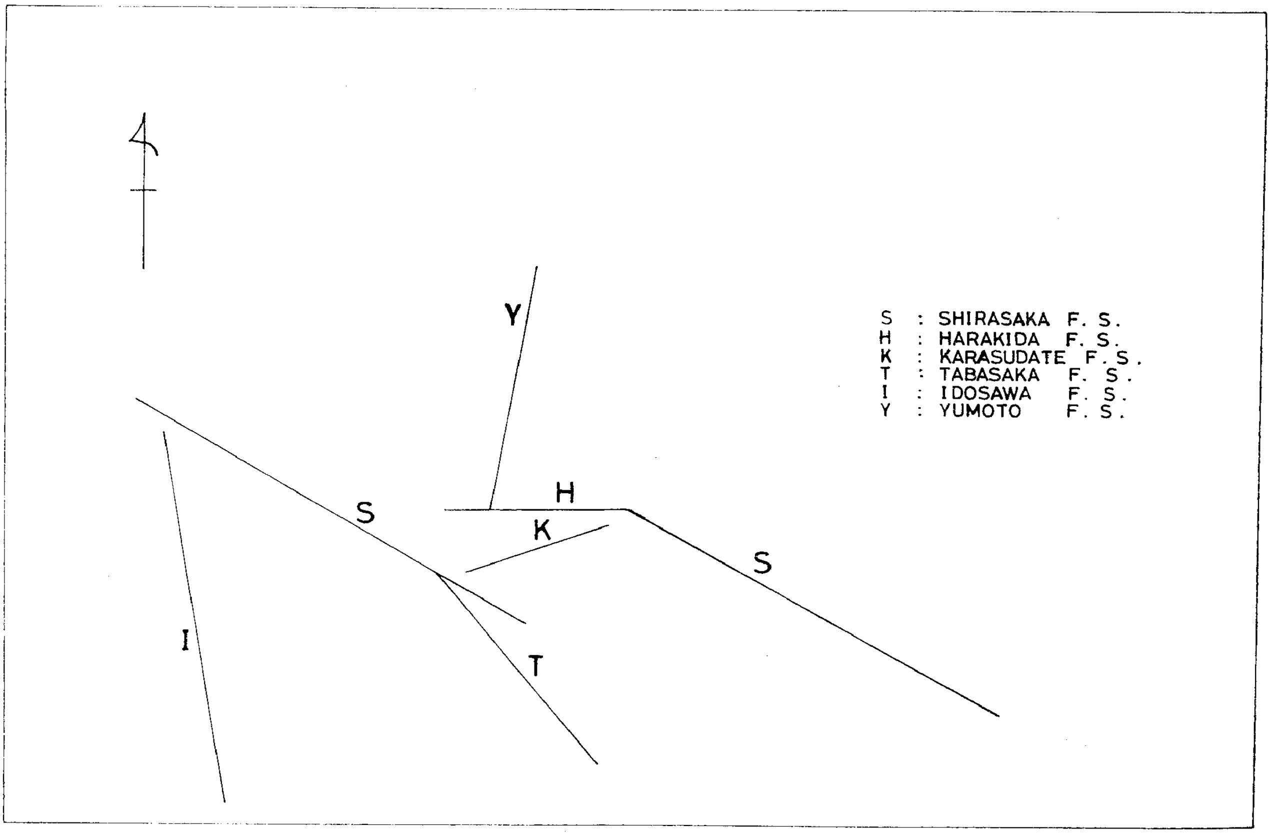


Fig. 17. Diagramatic fault pattern in the Joban coal-field

The *Harakida Fault Set* corresponds to the Shirasaka A Fault Set proposed previously by Mitsui (1969). This fault set includes the faults named Shirasaka, Harakida, Ena, Noda, Amakida and Yamada faults. There are many faults belonging to this fault set in the Iwaki North and Iwaki South areas, but few in the Futaba Area. This set is more limited in extension and displacement than the Shirasaka Fault Set.

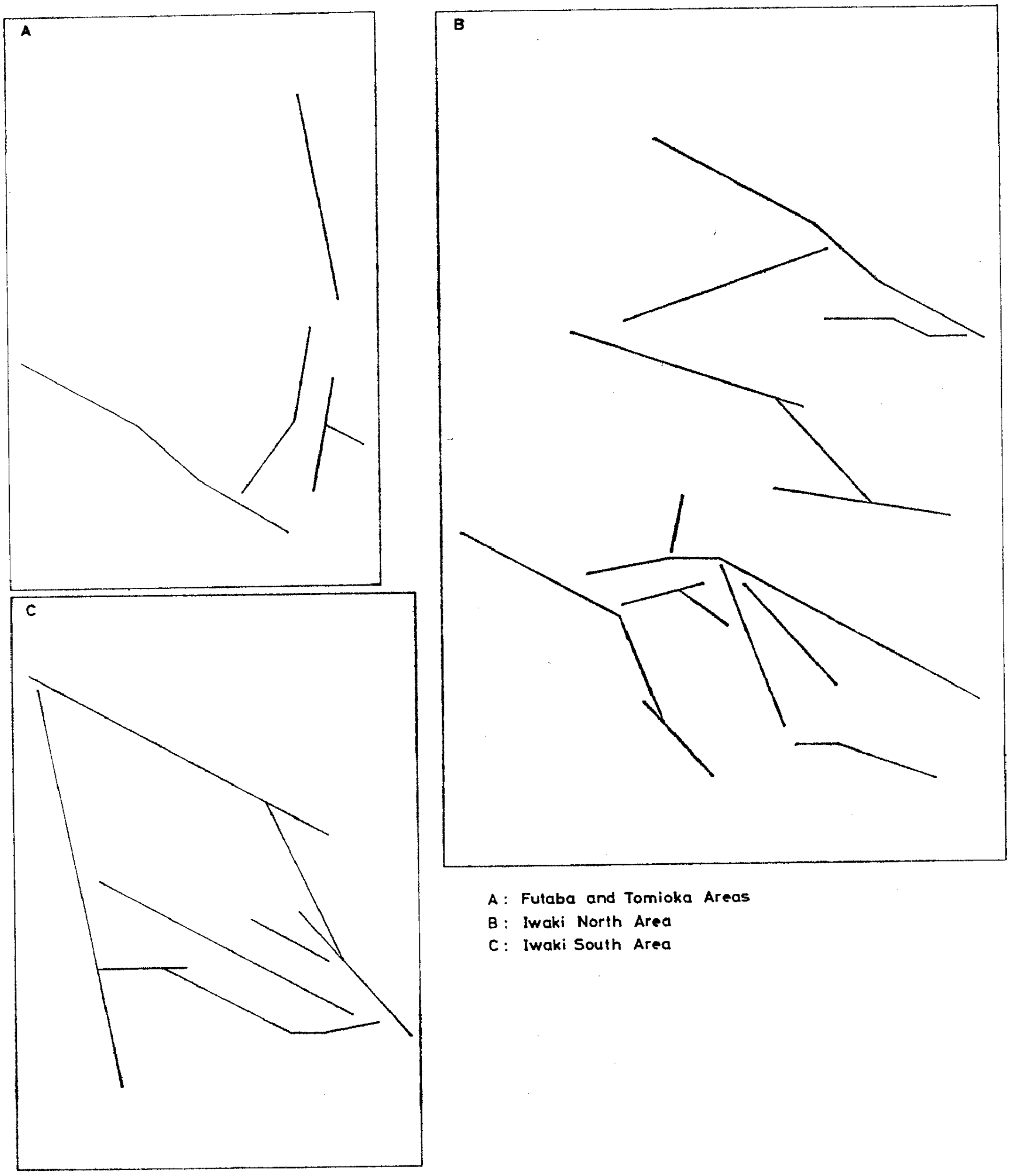


Fig. 18. Idealized fault pattern in selected areas

The *Shirasaka Fault Set* nearly corresponds with the Shirasaka B Fault Set proposed by Hoshino (1965) and used by Mitsui (1969). This set includes the Futatsuya, Yunotake, Shirasaka, Harakida, Komoda, Shimizu, Numanouchi, Ebata and Akai faults. These faults are the prominent ones and controlled the geological structures of the present area. As already stated, the Futatsuya and Yunotake faults developed prior to the sedimentation of the Tertiary rocks controlled the Tertiary sedimentary basin and differentiation of local environmental conditions. It is inferred that the faults of the Shirasaka Fault Set, which cut the Takaku Group, were formed by the reactivity of the prominent or main faults already referred to. The faults of this set are normal dip-slip or strike-slip faults. The majority are normal dip-slip faults from the following reasons, 1) most have developed dip-slip slicken-sides in the fault plane, 2) when judged from the stress field, most of the faults are gravity faults, 3) the faults of this set have an average dip of 55°–80°S, which is less than the general dip of wrench faults (de Sitter, 1956).

The *Karasudate Fault Set* is a normal fault set and corresponds to the Karasudate Fault Set named by Hoshino (1965) and used by Mitsui (1969). This set consists of the Karasudate, Iwaki, Ena, Okura and Nakadaira faults, etc. and shows trends at right angles to the Idosawa Fault Set. Most of the faults of this set were continuous with the faults of the Shirasaka and Harakida fault sets. Subsurface evidence indicates that there were faults in the basement rocks parallel to the Karasudate Fault Set. Since it is known that the fault set under consideration is a local one (Hoshino, 1965), it is considered that it was not so important prior to the deposition of the Iwaki Formation.

The *Idosawa Fault Set* is the same as the Idosawa Fault Set of Hoshino (1965) and the Sumiyoshi Fault Set of Mitsui (1969). This fault set is less extensive and not so conspicuous as the Shirasaka Fault Set, but is structurally more important because it is evidently closely related to the significant features of the Futaba disturbed zone (Mita, 1951), Tanakura sheared zone (Omori, 1958) and Hatagawa sheared zone (Hoshino, 1965) in the Abukuma massif. This fault set includes the Idosawa, Futaba, Sumiyoshi and Iwaide faults, among which only the Futaba is a reverse fault. The faults of this set show either dip-slip or strike-slip.

The *Tabasaka Fault Set* consists of normal faults and includes the Tabasaka, Aikawa, Omuro, Hirakubo, Yamazaki and Watanabe faults. This fault set shows in trend characters intermediate between the Idosawa Fault Set and the Shirasaka Fault Set.

The *Yumoto Fault Set* comprises normal dip-slip faults and is the same as the Yumoto Fault Set of Hoshino (1965) and Mitsui (1969). This fault set includes the Yumoto, Shinyashiki and Shobusaku faults; their trends are at right angles to the Harakida and Shirasaka Fault Sets. As shown by the Shinyashiki and Shobusaku faults, this fault set changes its strike to N40°–50°E in some cases. The faults of this set are few in the investigated area and amount to less than 10 percent of the whole (Table 3). Especially, there are few major faults of this set in the Iwaki South Area.

The relations among the six fault sets are given in the following paragraphs.

The Futaba thrust and the Idosawa fault of the Idosawa Fault Set have the strike of NNW-SSE parallel to the Hatagawa and Tanakura sheared zones bordering respectively the eastern and western margins of the Abukuma massif. It is considered (Kitamura, 1963) that the oldest structural trend in Northeast Japan has strike of NNW-SSE which is considered to correspond with the trend of the Paleozoic geantincline and changed into a fault by the Late Cretaceous orogenic movement. In the basement rocks, there are found faults parallel to the Karasudate Fault Set, but all of them are of small scale and have limited extension.

From the patterns and characteristic features of the faults mentioned above, it is considered that the old faults that developed in the basement rocks prior to the sedimentation of the Shiramizu Group had rhombic structure, and consisted of the Idosawa and Shirasaka Fault Sets (Fig. 19–A). The consideration on the faults that cut the Tertiary rocks, suggests that the faults of the Harakida, Shirasaka and Karasudate fault sets were originally intermittently active and formed under the same stress field of the Shirasaka, Harakida and Ena faults. Among the faults cutting the Tertiary sedimentary rocks, those of the Idosawa Fault Set attain only 15 percent of the whole, whereas those of the Shirasaka, Karasudate and Harakida fault sets more than 60 percent. This fact strongly suggests that those faults occurred by the orogenic movement of post-Takaku and pre-Izumi time were strongly influenced by the pre-existing faults with WNW-ESE strike in comparison to the faults of NNW-SSE strike (Fig. 19-B).

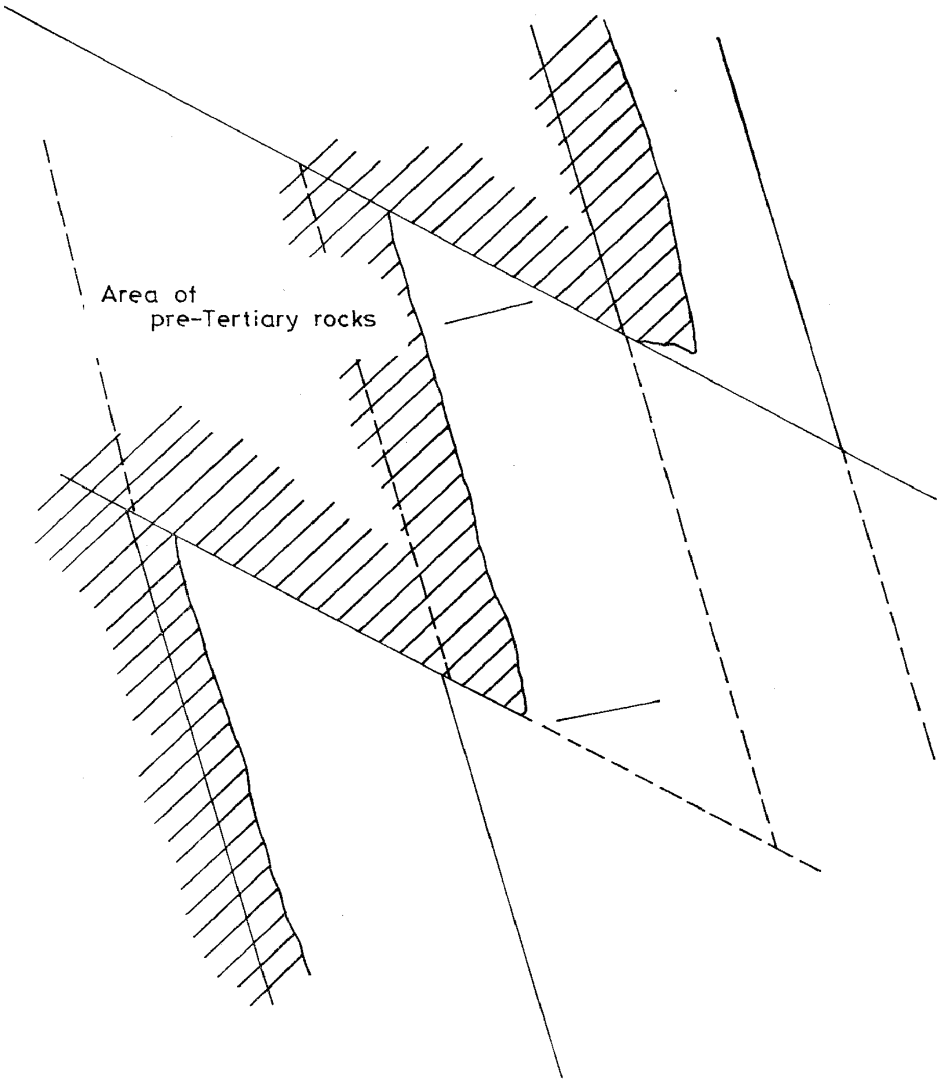


Fig. 19-A

Figs. 19 A–B. Explanation of the structural development of the fracture system
A. After the earlier faulting or pre-Shiramizu time
B. After the later faulting or pre-Izumi time

III. ANALYSIS OF THE STRESS FIELD

In the foregoing paragraph it was explained that the faults cutting the Tertiary sedimentary rocks developed due to the influence of the structure of the basement. However, nothing was stated on what movements of the basement exerted the influence for the development of the younger faults. As a method to interpret the movements an analysis of the stress field was undertaken. Recently, many authors have used the results of analysis of the stress field based upon minor faults to interpretate the development of geological structures (Hirayama and Kakimi, 1965; Kakimi, *et al.*, 1966; Kimura, 1966; Kimura *et al.*, 1968; Fujita, *et al.*, 1965; Kutsuzawa and Fujita, 1966; Hoshino, 1967; Kodama, 1968; Komatsu and Watanabe, 1968; Kakimi, 1968; Kinugasa, *et al.*, 1969; Mitsui, 1969).

The relation between the geologic structure, that is to say, the faults and stress field at the respective localities of the faults is given in Table 6.

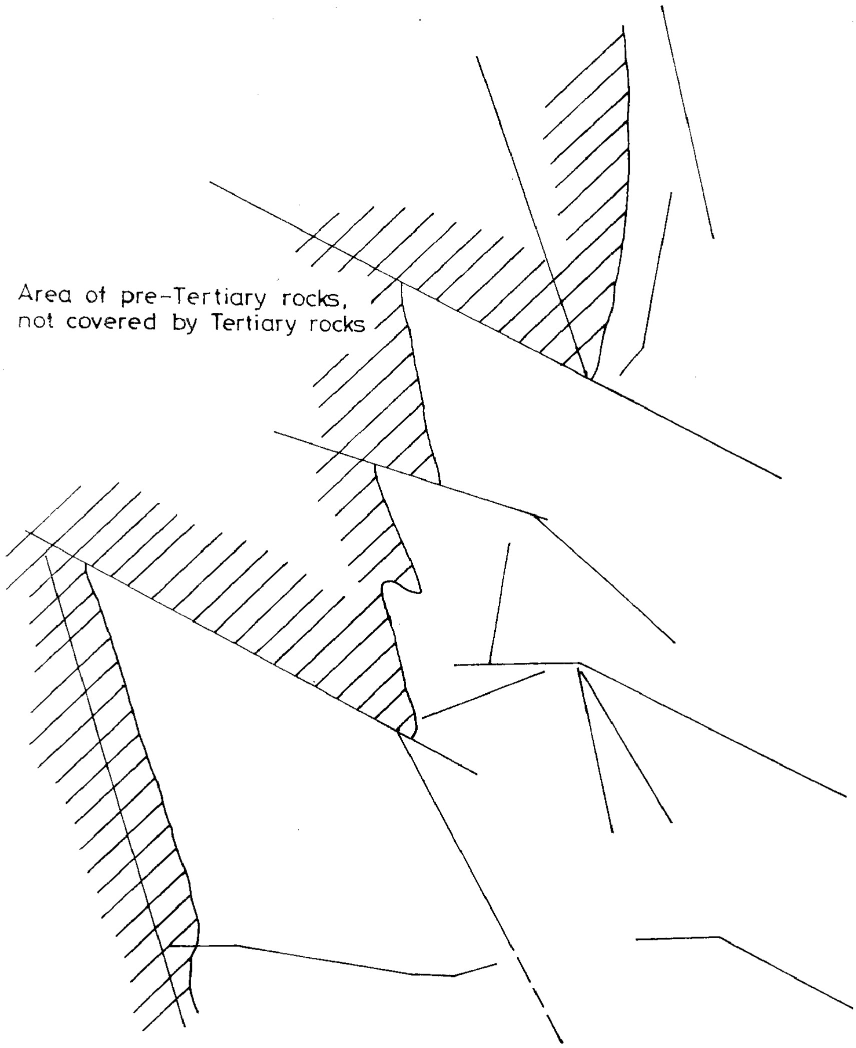


Fig. 19-B

ANALYSIS OF THE PRINCIPAL STRESS (Fig. 20 and Table 6)

Analysis of the stress field was undertaken of every formations of the Tertiary System ranging from the Iwaki Formation up to through the Shimotakaku Formation. A part of the results have already been reported by Mitsui (1969).

1. IWAKI NORTH AREA

In the area north of the Shirasaka fault, from the analysis of the principal stress at the localities of T-35 and I-7 (Iwaki), T-42 (Shirasaka), I-4 and I-6 (Kameno-o), T-12 and T-26 (Honya Mudstone M.), T-34 and T-11 (Misawa Sandstone M.) and I-9 and I-10 (Shimotakaku F.), the following features were recognized in the formations from the Iwaki to the Shimotakaku namely, the minimum compressive principal stress (σ_1) lies with angle of 15° towards the north or south, the intermediate principal stress (σ_2) lies with low angle 10°–30° towards the east or west, and that, the maximum compressive principal stress (σ_3) acts with high angle of 50°–80° towards the east or west. The general strike and dip at the localities mentioned above are N10°–30°W and 10°–15°E respectively. At the localities where the general strike and dip are N70°E–N70°W and 10°–20°N

Table 6. Statistical relationship of the fault sets at the respective localities

Area	Loc. nos.	Formation & Member	Conjugate Set		Principal Stress			shear angle (2θ°)	Note
					σ1	σ2	σ3		
Tomioka & Futaba Areas	H-1	Kameno-o	22∠75	188∠70	14∠ 2	106∠22	282∠68	36	
	H-2	Kameno-o	142∠38	257∠41	23∠68	197∠22	290∠ 2	67	R.
	H-3	Goyasu	357∠36	316∠52	152∠48	10∠36	267∠20	32	R.
	H-4	Iwaki	51∠70	243∠70	237∠ 1	328∠14	150∠76	42	
	H-5	Sekinoue	93∠65	233∠80	252∠ 8	154∠46	349∠43	53	J.
	T-40	Kurosuno	63∠55	268∠75	259∠ 4	351∠22	157∠67	55	
	T-41	Shirasaka	28∠60	233∠85	222∠13	320∠30	110∠58	42	
	I-1	Kurosuno	118∠88	229∠54	88∠18	205∠52	344∠30	74	
	I-2	Kurosuno	293∠60	148∠60	132∠10	230∠36	27∠52	52	
	I-24	Pre-Creta.	266∠70	134∠80	110∠ 2	206∠56	17∠34	58	
	I-3	Iwaki	298∠65	173∠85	148∠11	256∠58	50∠29	60	
Iwaki North Area	I-4	Kameno-o	353∠55	193∠60	184∠ 2	274∠14	84∠76	68	
	I-5	Nakayama	207∠65	93∠80	62∠ 8	166∠58	327∠30	73	
	I-6	Kameno-o	333∠65	205∠60	356∠ 2	266∠40	92∠50	74	
	I-7	Iwaki	3∠88	163∠60	354∠13	94∠32	242∠55	39	
	I-8	Mizunoya	328∠70	115∠78	131∠ 2	36∠44	224∠46	46	
	I-9	Shimotakaku	33∠65	204∠50	29∠ 6	121∠ 6	246∠82	66	
	I-10	Shimotakaku	43∠70	203∠50	34∠ 8	128∠16	274∠72	63	
	I-11	Kameno-o	283∠50	113∠69	108∠10	200∠ 8	330∠78	61	
	I-12	Kameno-o	73∠45	243∠70	248∠12	156∠ 6	42∠76	65	
	I-13	Nakayama	13∠58	153∠55	354∠ 2	84∠28	261∠62	76	
	I-14	Honya	8∠70	213∠70	20∠ 0 200∠ 0	29∠30	110∠60	47	
	I-15	Shimotakaku	23∠80	223∠70	32∠ 4	301∠32	130∠58	36	
	I-16	Nakayama	21∠70	143∠68	176∠ 2	84∠50	261∠40	70	
	I-17	Shimotakaku	3∠88	193∠65	8∠10	275∠18	130∠68	28	
	I-18	Honya & Misawa	23∠80	193∠50	19∠14	112∠ 8	228∠72	50	
	I-19	Honya & Misawa	83∠50	193∠70	224∠12	122∠42	327∠46	88	
	I-20	Nakayama	346∠80	161∠55	344∠12	74∠ 6	190∠78	46	
	I-21	Nakayama	333∠60	143∠60	148∠ 0 328∠ 0	58∠ 8	238∠82	60	
	I-22	Honya	323∠65	153∠50	328∠ 6	238∠ 6	102∠82	68	
	I-23	Honya	23∠80	213∠80	28∠ 0	298∠24	118∠66	22	
	T- 1	Numanouchi	7∠86	145∠78	348∠ 4	86∠66	256∠23	44	J.
	T- 2	Numanouchi	331∠78	197∠72	353∠ 2	256∠54	86∠34	54	J.

Table 6. Continued

Iwaki North Area	T- 3	Numanouchi	353∠84	216∠81	14∠ 2	280∠70	105∠20	44	J.
	T- 4	Shimotakaku	11∠75	201∠76	196∠ 1	287∠14	106∠77	31	
	T- 5	Shimotakaku	358∠78	163∠60	349/18	84∠16	231/72	44	
	T- 6	Nakayama	358∠72	163∠66	352∠ 2	82∠18	250/72	45	
	T- 7	Nakayama	13∠76	211∠66	23∠ 4	291∠22	124∠68	42	
	T- 8	Misawa	355∠70	167∠60	350∠ 5	81∠ 6	221∠82	50	J.
	T- 9	Misawa	60∠80	191∠66	36∠ 6	136∠54	303∠36	58	J.
	T-10	Shimotakaku	343∠52	138∠70	149∠ 7	55∠20	263∠69	62	
	T-11	Misawa	10∠64	140∠63	166∠ 0 346∠ 0	76∠40	256∠50	72	J.
	T-12	Honya	338∠66	169∠71	164∠ 2	254∠12	69∠78	45	J.
	T-13	Misawa	81∠52	210∠76	232∠13	132∠38	338/48	70	
	T-14	Iwaki	20∠60	180∠87	188∠13	92∠28	302∠59	38	
	T-15	Honya	344∠74	196∠66	0∠ 4	267∠36	95∠54	50	
	T-16	Honya	322∠60	198∠77	172∠ 9	272∠48	74∠41	68	
	T-17	Mizunoya	15∠58	178∠73	184∠ 8	93∠18	296∠71	52	
	T-18	Mizunoya	12∠72	235∠70	34∠ 1	303∠46	124∠44	58	
	T-19	Mizunoya	7∠70	162∠60	356∠ 2	87∠24	258∠67	54	J.
	T-20	Misawa	26∠72	162∠72	182∠ 2	91∠48	274∠42	57	
	T-21	Kamitakaku	340∠68	194∠72	178∠ 2	269∠38	87∠52	52	J.
	T-22	Honya	323∠70	168∠77	154∠ 2	245∠30	58∠60	38	
	T-23	Mizunoya	20∠65	180∠50	12∠ 4	103∠14	264∠76	67	
	T-23	Kameno-o	330∠60	210∠60	180∠ 1	272∠40	90∠50	81	
	T-24	Mizunoya	346∠71	188∠61	356∠ 5	264∠24	98∠66	53	
Iwaki North Area	T-25	Kameno-o	36∠74	213∠74	212∠10	124∠ 4	12∠80	51	
	T-25	Kameno-o	18∠58	201∠68	200∠ 5	290∠ 2	38∠86	54	
	T-26	Kamiyata	17∠75	195∠75	196∠ 0 16∠ 0	106∠ 2	286∠88	30	
	T-26	Honya	335∠65	170∠70	162∠ 2	253∠17	67∠73	48	
	T-27	Nakayama	5∠56	191∠70	189∠ 8	280∠ 6	56∠82	54	
	T-28	Nakayama	7∠82	167∠78	358∠ 2	90∠44	266∠48	28	
	T-28	Nakayama	333∠82	176∠66	344∠ 8	249∠32	86∠58	38	
	T-29	Misawa	9∠64	145∠82	164∠ 8	64∠50	264∠40	55	
	T-30	Misawa	337∠54	155∠62	157∠ 4	66∠ 2	296∠86	64	
	T-31	Nakayama	358∠74	202∠64	8∠ 4	277∠26	106∠64	48	
	T-32	Nakayama	340∠66	173∠72	168∠ 4	258∠16	66∠74	45	
	T-33	Nakayama	11∠62	173∠85	181∠12	86∠26	294∠61	38	
	T-34	Misawa	338∠72	195∠67	356∠ 2	264∠40	86∠51	52	
	T-35	Iwaki	213∠80	356∠60	196∠10	293∠38	94∠51	56	
	T-36	Iwaki	153∠85	338∠63	155∠11	64∠ 6	304∠78	34	
	T-37	Honya	321∠73	143∠80	142∠ 4	232∠ 4	11∠85	28	

Table 6. Continued

	T-38	Iwaki	98∠74	283∠70	100∠ 2	9∠ 6	207∠84	37	
	T-39	Iwaki	98∠72	283∠68	100∠ 2	10∠ 4	198∠86	42	
	T-42	Shirasaka	317∠80	209∠60	350∠11	241∠56	88∠32	80	
	K- 3	Kamiyata	188∠72	358∠58	183∠ 6	274∠10	62∠78	50	
	K- 5	Kameno-o	49∠70	219∠68	226∠ 2	135∠12	313∠60	43	
	K-20	Mizunoya	121∠60	278∠72	291∠10	196∠22	45∠66	53	
	K-21	Kameno-o	353∠60	166∠54	350∠ 2	80∠ 4	222∠85	66	
	K-22	Honya	353∠70	133∠83	152∠ 6	52∠54	248∠35	48	
	K-23	Nakayama	353∠70	185∠76	179∠ 2	270∠18	80∠72	36	
	K-25	Kameno-o	33∠72	191∠50	24∠12	118∠18	264∠68	62	
Iwaki South & Taga Areas	K- 1	Mizunoya	332∠60	164∠65	340∠ 2	249∠10	53∠80	56	
	K- 2	Nakayama	330∠70	123∠78	136∠ 4	42∠38	230∠52	42	
	K- 4	Kunugidaira	18∠72	180∠65	8∠ 4	100∠20	266∠70	46	
	K- 6	Goyasu	69∠60	224∠70	235∠ 4	144∠26	336∠64	54	
	K- 7	Kameno-o	19∠70	214∠70	26∠ 1	298∠18	118∠72	43	
	K- 8	Kameno-o	341∠61	181∠60	350∠ 1	260∠16	82∠74	61	
	K- 9	Kurosuno	347∠70	173∠80	58∠78	261∠10	352∠ 4	30	
	K-10	Kameno-o	283∠80	136∠82	298∠ 2	210∠58	27∠32	36	
	K-11	Nakayama	0∠80	146∠76	167∠ 1	75∠54	252∠36	40	J.
	K-12	Nakayama	3∠80	158∠62	352∠ 8	86∠30	246∠58	45	J.
	K-13	Nakayama	335∠68	193∠70	175∠ 1	265∠40	84∠50	56	J.
	K-14	Nakayama	11∠80	183∠68	8∠ 4	99∠11	256∠78	34	
	K-15	Nakayama	176∠82	298∠78	146∠ 2	242∠70	56∠20	60	J.
	K-16	Goyasu	346∠70	143∠64	334∠ 2	66∠24	238∠66	51	J.
	K-17	Kunugidaira	13∠86	209∠56	20∠14	286∠20	146∠66	41	
	K-18	Kamikamado	328∠82	204∠80	354∠ 2	263∠72	86∠18	58	J.
	K-19	Kurosuno	353∠70	155∠72	164∠ 1	73∠23	255∠68	42	
	K-24	Kunugidaira	343∠70	133∠50	332∠ 9	64∠12	202∠76	65	
	K-26	Kurosuno	16∠63	150∠71	172∠ 3	78∠42	266∠48	63	J.
	K-27	Kurosuno	357∠66	184∠80	18∠ 6	272∠10	58∠78	35	J.
	K-28	Kurosuno	327∠84	141∠70	324∠ 4	54∠12	216∠78	24	
	K-29	Nakosonoseki	67∠65	253∠75	250∠ 4	341∠ 6	114∠80	41	
	K-30	Kurosuno	11∠75	193∠62	12∠ 6	282∠ 2	168∠84	44	
	K-31	Kameno-o	11∠70	203∠74	197∠ 2	288∠16	103∠74	38	

respectively, that is, at I-14 (Honya Mudstone M.), T-6 (Nakayama F.), T-3 (Numanouchi F.) and T-4 (Shimotakaku F.), the principal stress shows that σ_1 lies with nearly horizontal angle towards the north or south, σ_2 acts with angle of 30° towards the east or west and σ_3 with high angle of 60°–80° towards the east or west.

In such a manner, it is recognized in the area north of the Shirasaka fault the directions of the principal stress axes are almost the same in the formations ranging from the Iwaki to the Shimotakaku regardless of their strike and dip. Namely, the stress field in which σ_3 acts with high angle towards the east or west was the main and primary one, whereas the stress field in which σ_3 lies with high angle towards the north or south was secondary.

In the south of the Shirasaka fault, the stress field at localities of T-14 and T-36 (Iwaki F.), T-17, T-18, T-23 and T-24 (Mizunoya F.), T-23, I-20, K-5 and K-21 (Kameno-o F.), K-22, T-16 and I-18 (Honya Mudstone M.), K-3 (Kamiyata Sandstone M.), T-20 (Misawa Sandstone M), I-13 (Nakayama F.) and T-21 (Kamitakaku F.), shows that the direction of the principal stress axes is almost the same in the formations ranging from the Iwaki up to and including the Kamitakaku. Namely, σ_1 acts nearly in north or south direction with low angle (0°–25°), σ_2 is nearly in east or west direction with low angle (0°–30°) and σ_3 is nearly in east or west direction with high angle (60°–80°). However, the stress fields at localities of K-20 (Mizunoya F.), I-11 and T-25 (Kameno-o F.), T-37 (Honya Mudstone M.) and T–13 (Misawa Sandstone M.) show that σ_3 acts with high angle towards the north or south. The general strike and dip in above localities are N-S to N30°W and 10°–30°E respectively.

At the localities where the general strike and dip are N70°W-N70°E and 10°–20°N respectively, that is, at localities I-22 and I-23 (Honya Mudstone M.), T-29 and T-30 (Misawa Sandstone M.) and I-17 and T-10 (Shimotakaku F.), σ_1 acts with angle of 0°–10° towards the north or south, σ_2 lies with low angle (0°–30°) towards the east or west and σ_3 acts with high angle (60°–85°) towards the east or west. Only at the locality I-20 (Nakayama F.), σ_3 acts with high angle towards the north or south.

As described above, the direction of the principal stress axes of the stress fields in the south of the Shirasaka fault is almost the same from the Iwaki Formation up to and including the Shimotakaku Formation regardless of the strike and dip of the strata. Nemely, the stress in which σ_1 acts with low angle towards the north or south, σ_2 with low angle towards the east or west and σ_3 lies with high angle towards the east or west was the main and primary one, whereas the stress field in which σ_3 acts with high angle towards the north or south was secondary.

2. IWAKI SOUTH AREA

At the localities of K-4 (Kunugidaira F.), K-16 (Goyasu F.), K-1 (Mizunoya F.), K-7 and K-8 (Kameno-o F.), K-2, K-11, K-12, K-13, K-14 and K-15 (Nakayama F.) and K-18 (Kamikamado F.), the direction of the principal stress axes are almost the same. Namely, σ_1 lies with low angle (0°–15°) towards the north or south, σ_2 acts with low angle (10°–30°) towards the east or west and σ_3 lies with high angle (50°–80°) towards the east or west. Whereas, at K-17 and K-24 (Kunugidaira F.), K-6 (Goyasu F.), K-10 (Kameno-o F.), σ_3 lies with high angle towards the north or south.

In the Iwaki South Area as in the Iwaki North Area it is considered that the stress field in which σ_3 lies with high angle (50°–80°) towards the east or west was the main and primary one and that the stress field in which σ_3 lies with high angle towards the north or south was secondary.

RELATION BETWEEN THE GEOLOGICAL STRUCTURES AND THE STRESS FIELD

In the foregoing section, the analysis of the stress field developed in the present area was described. It is also possible to analyse the mechanism making the geological structures of the area from the acquired stress field. However, in such case attention must be given with regard to the time at which the stress field was formed.

As mentioned in the section on the Fold Structures, the Iwaki syncline in the Iwaki North Area is displaced by the Shirasaka Fault Set. This proves that the faults in the investigated area were formed after the formation of the fold structures which developed by the tectonic movement that occurred after the deposition of the Takaku Group and before that of the Izumi Group. Also, the analysis indicate that the faults were not formed when the strata were in a horizontal position. Therefore, it is considered that the stress fields analysed from the minor faults, which were probably formed under the same conditions as the major faults, were embryonal at the time of the folding of the strata after deposition of the Takaku Group. Accordingly, it is consistent to discuss the origin of the faults cutting the Tertiary rocks based upon the results of the stress field analysed from the minor faults.

As stated in the foregoing paragraph, in the stress field due to the later tectonic movement in the Iwaki North and Iwaki South Areas, the stress field in which σ_3 acts with high angle towards the east or west was the main and primary one, whereas the stress field in which σ_3 lies with high angle towards the north or south was secondary. Because the stress field was formed during the later tectonic movement, it is considered that the faults cutting the Tertiary sedimentary rocks developed under the strong influence of the basement faults of WNW-ESE strike in comparison with those of NNW-SSE strike. And, that the faults of the Shirasaka, Harakida and Karasudate fault sets, in comparison with those of the Idosawa and Yumoto fault sets were formed dominantly in the Tertiary sedimentary rocks in the Iwaki North and Iwaki South Areas.

From the standpoint of the stress field the consideration on the origin of the main faults developed in the investigated area are shown in Table 6.

Futaba Thrust Fault; From the stress fields of H-2, H-3, σ_1 acts with high angle to the horizontal plane in comparison with σ_2 and σ_3 and the fault is a thrust fault formed by horizontal compression.

Akai Fault; From the stress fields of I-14 and T-35 lies nearly on the vertical plane and this shows that the Akai fault is a gravity fault.

Numanouchi Fault; From the stress fields of I-9 and T-5, σ_3 lies with high angle in comparison of σ_1 and σ_2, and the slicken-side coincides with the dip-direction of the fault plane. Therefore, the Numanouchi fault is a gravity fault.

Shimizu Fault; Because σ_3, in the stress fields of I-10 and T-4, acts with high angle and the slicken-side shows dip-slip, the Shimizu fault is a gravity fault.

Yumoto Fault; From I-7, it seems that the Yumoto fault is a gravity fault.

Shirasaka Fault; From the stress fields of T-24, I-12 and I-17 the Shirasaka fault is a gravity fault because σ_3 acts with high angle in comparison with σ_1 and σ_2. Further, this fault has the nature of a strike-slip fault because, for exmaple, in T-9, σ_2 acts with high angle as compared with σ_3. On the other hand, the slicken-side coincided with the dip-direction of the fault plane. Accordingly, the Shirasaka fault is a gravity fault, but with local characters of a strike-slip fault.

Karasudate Fault; From the stress fields of T-17, T-23 and K-3, σ_1 and σ_2 lie with low angle and σ_3 acts with high angle. Also, the slicken-side shows dip-slip. Hence, the Karasudate fault is a gravity fault.

Sumiyoshi Fault; In the stress fields of I-11 and I-25, σ_3 acts with high angle in comparision with σ_1 and σ_2. Whereas, in T-16, σ_2 acts with higher angle than σ_3. Accordingly, the Sumiyoshi fault has characters both of gravity fault and strike-slip fault. All directions of the slicken-side on the fault plane coincide with the strike-direction of the fault plane.

Harakida Fault; From T-20, I-22, and T-32 both σ_1 and σ_2 acts with low angle against the horizontal plane and σ_3 lies with high angle, and the slicken-side corresponds with the dips of the fault plane. Hence, the Harakida fault is a gravity fault.

Yamada Fault; The stress field of K-6, K-7 and K-24 shows that σ_1 and σ_2 act with low angle and σ_3 acts with high angle. Therefore, the Yamada fault is a gravity fault.

As mentioned above, from the stress fields, it is inferred that most of the main faults in the investigated area belong to gravity faults and from the orientation of the stress ellipsoid, those faults were formed by vertical tectonic movement. From the stress fields, most of the faults which belong to the Harakida, Shirasaka, Karasudate and Yumoto fault sets are gravity faults with dip-slip, whereas the Idosawa and Tabasaka fault sets were either gravity or strike-slip faults.

ANGLE OF SHEAR PLANE

It is known that the angle of the shear plane is closely related with the type of the fault. For example, Hirayama and Kakimi (1965) noted that the angle of normal shear fractures are 40° in average and that those of the reverse shear fractures are 70°. Also, Kodama (1968) reported that the normal is less than 40° and the reverse is 80° in average. Further, they considered that the normal faults at Cho-ga-saki and Joga-shima, Miura Peninsula, Kanagawa Prefecture, were formed under the tensile stress field and that the reverse faults were formed under the compressive stress field.

SHEAR PLANE ANGLE	NOS.	%
0 - 9	0	0
10 - 19	0	0
20 - 29	4	5.6
30 - 39	11	15.2
40 - 49	15	20.8
50 - 59	19	26.4
60 - 69	14	19.4
70 - 79	6	8.3
80 - 89	3	4.2
total	72	99.9

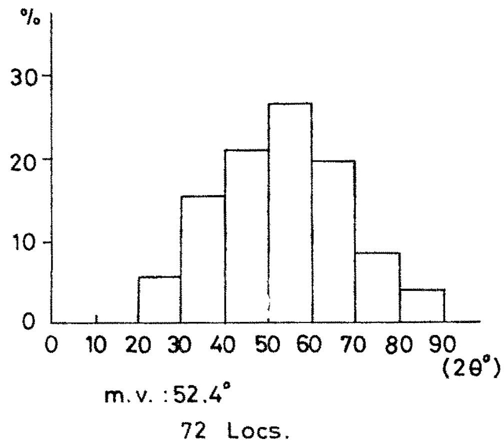


Fig. 21. Shear plane angle of the normal shear fracture in the Iwaki North Area

In the investigated area, the angle of the normal shear fractures in the Iwaki North Area (Fig. 21) are 52.4° (of 72 localities), 49.3° in the Iwaki South Area (Fig. 22) (of 16 localities) and average 51.9° in both areas (Fig. 23). Namely, the angles in the surveyed area average from 49° to 52° degrees and this sum is larger than the ones (40° or less than 40°) reported by Hirayama and Kakimi (1965) and Kodama (1968). It is known that the angles of the shear plane increase with the increase in confining pressure and come nearer to 90 degrees (Hoshino, 1966). Therefore, it is thought that the normal faults in the investigated area developed under higher confining pressures, contrary to the opinions of Hirayama and Kakimi (1965) and Kodama (1968) who state that normal faults are due to tension.

SHEAR PLANE ANGLE	NOS.	%
0 - 9	0	0
10 - 19	0	0
20 - 29	0	0
30 - 39	2	12.5
40 - 49	6	37.5
50 - 59	5	31.3
60 - 69	3	18.8
70 - 79	0	0
80 - 89	0	0
total	16	100.1

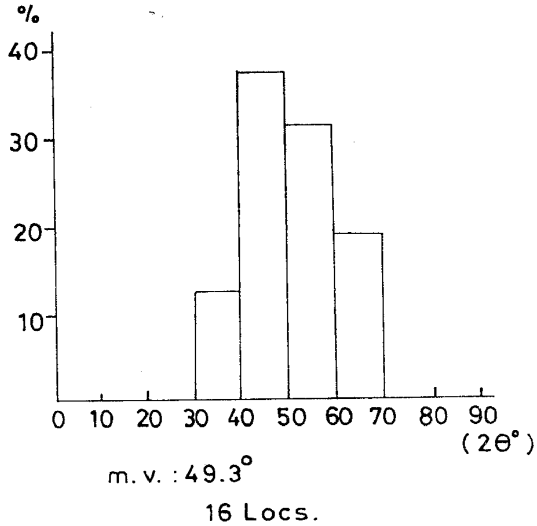


Fig. 22. Shear plane angle of the normal shear fracture in the Iwaki South Area

SHEAR PLANE ANGLE	NOS.	%
0 - 9	0	0
10 - 19	0	0
20 - 29	4	4.5
30 - 39	13	14.8
40 - 49	21	23.0
50 - 59	24	27.3
60 - 69	17	19.3
70 - 79	6	6.8
0 - 9	3	3.4
total	88	100.0

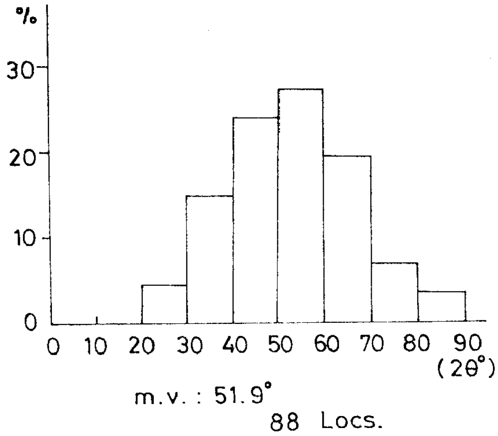


Fig. 23. Shear plane angle of the normal shear fracture in the Iwaki North and Iwaki South areas

IV. JOINTS

The writer analysed not only the stress field of the minor faults, but also studied the joints. Joints as the faults are closely related to the geological structure. Many authors have reported on the joints associated with the regional geological structures (Hoshino, 1965; Hirabayashi, 1964; Murai, 1965 a, b, 1966, 1967; Yamaguchi, 1965 ; Hirano, 1969; Kitamura, 1962).

MEAN DENSITY

For the analysis of joints, first, the mean density of the joints at each locality was determined because of its usefulness to interpretate the development of joints. Here, the mean density is defined as the ratio of the number of occurrence of joints to the interval in meters (number/meter) (Fig. 24).

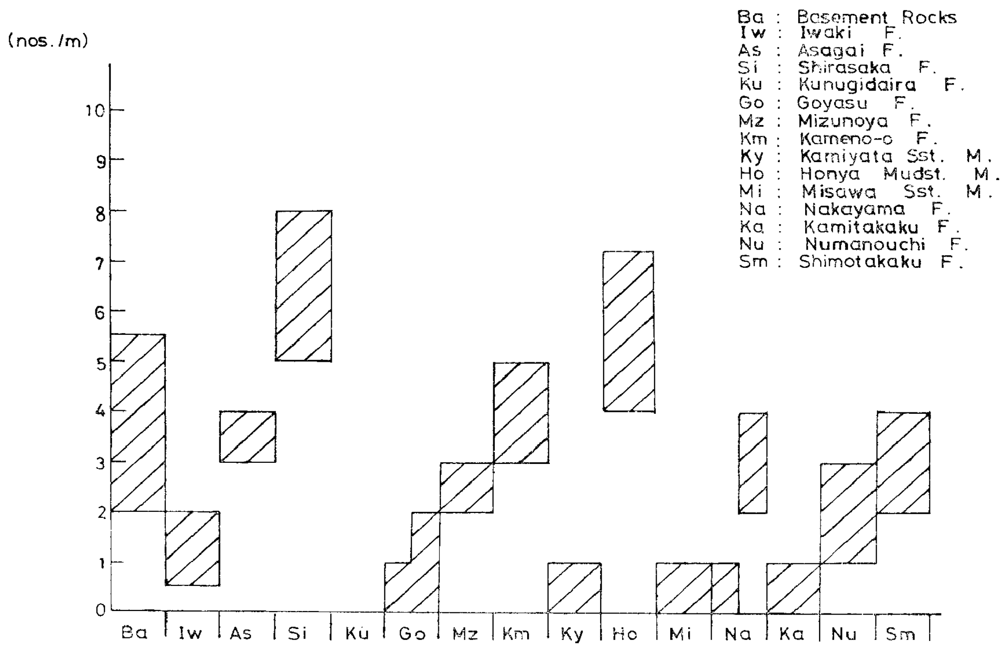


Fig. 25. Mean density of joints in the Iwaki North Area.

1. IWAKI NORTH AREA (Fig. 25)

The mean density in the basement rocks, which consists of granitic rocks and the Abukuma metamorphic rocks, shows the values of 2.0–5.0 numbers/meter.

In the Iwaki Formation which is composed mainly of conglomerate-bearing coarse grained sandstone and fine grained sandstone, the values are 0.5–2.0, and, generally, less than 1.0 in the former and near to 2.0 in the latter. The values of the mean density are 3.0–4.0 in the fine grained sandstone of the Asagai Formation and ranges from 5.0 to 8.0 in the shaly mudstone of the Shirasaka Formation. In the Shiramizu Group the sediments change gradually from coarse to fine grained in the order of the Iwaki, Asagai and Shirasaka formations in upward succession, whereas from the figures stated above, the mean density of the joints indicate larger values towards the upper formations, and this shows that the joints are better developed in the rocks composed of fine grained sediments.

The Goyasu Formation in this area, gave the values of 0–2.0 in mean density, and was near zero in the coarse grained sandstone of the lower part and 2.0 in the fine grained sandstone of the upper part of the formation. The values are 2.0–4.0 in the Mizunoya Formation. But, for an alternation of mudstone and sandstone (more dominant), the mean density is 2.0 for the sandstone and 3.0 for the mudstone. In this case the mudstone has values larger than those of the sandstone. The Kameno-o Formation which consists mainly of shale gives 3.0–5.0 in the mean and shows the values larger than those of the Mizunoya Formation. The Honya Mudstone Member of the Taira Formation ranges from 4.0 to 7.2 in mean density. On the contrary, the Kamiyata and Misawa Sandstone members, which are composed mainly of medium to coarse grained sandstone, and the Ishimoriyama Tuff-breccia Member of the Taira Formation, the mean density is below 1.0 in general and less than 2.0 even in maximum.

Tuffaceous rocks of the upper part of the Nakayama Formation give the values of 2.0–4.0 in density and usually, the values are smaller for sandy materials and larger for the muddy ones.

In the Takaku Group the mean density is less than 1.0 for the coarse grained sandstone of the Kaimitakaku Formation, 1.0–3.0 for the fine grained sandstone of the Numanouchi Formation and 2.0–.40 for the tuffaceous siltstone of the Shimotakaku Formation.

Therefore, it is recognized that the mean density of joint gradually increase with for the lithologic character in the order of conglomerate-bearing coarse grained sandstone-coarse sandstone-fine grained sandstone-muddy rocks and also that the joints have better development in the rocks composed of finer-grained sediments.

2. IWAKI SOUTH AREA (Fig. 26)

In the granitic rocks and metamorphic rocks the mean density value is 2.0–5.0. In the coarse grained sediments of the Kunugidaira and Goyasu formations, the upper part of the Mizunoya Formation, the Kamiyata Sandstone Member of the Taira Formation, the lower part of the Nakakyama Formation and the Kamikamado Formation, the mean density ranges from zero to 2.0, but rarely 2.0–3.0. Whereas in the muddy rocks of the lower part of the Mizunoya Formation, the Kameno-o Formation, the Honya Mudstone Member and the upper part of the Nakayama Formation, the values are 2.0–4.0. The siltstone of the Shimotakaku Formation shows values below 2.0. In the siltstone of the Izumi Group the density values are from zero to 2.0, and the majority are 1.0 and are most stable.

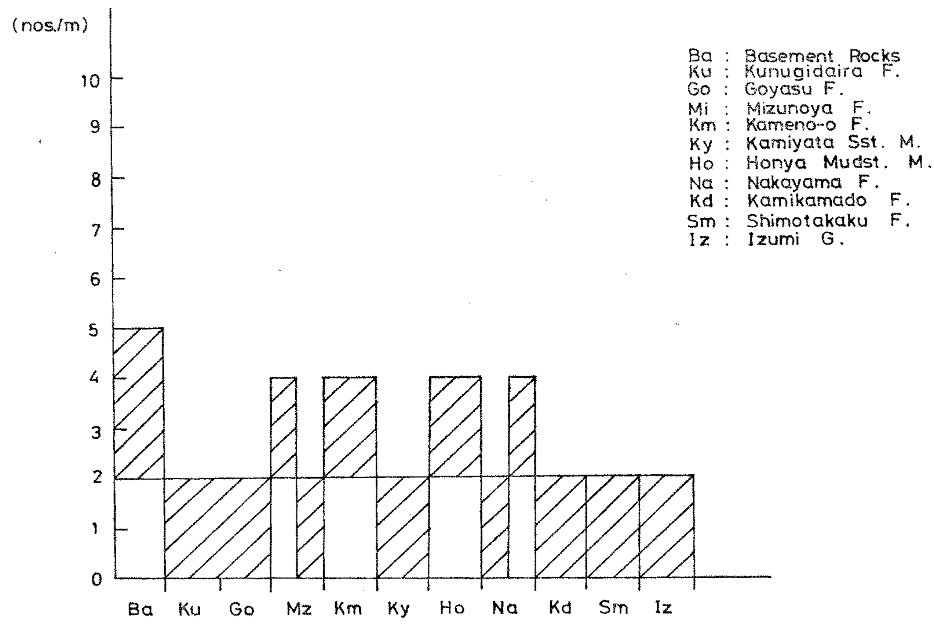


Fig. 26. Mean density of joints in the Iwaki South Area

From the above description, the following two points are recognized in this area, that is; 1) There is difference of the mean density between the Shimotakaku Formation and the Izumi Group. 2) When compared with the Iwaki North Area, the mean density of the muddy rocks of each formation in this area is generally small. From this it is inferred that the Iwaki South Area had been subjected to less influence of the tectonic movements before the deposition of the Izumi Group compared with the Iwaki North Area.

3. FUTABA AND TOMIOKA AREAS (Figs. 24 and 27)

The Futaba Group consists mainly of coarse grained sandstone and the mean density values are from 1.0 to 2.1 numbers/meter. The value is below 1.0 in the Iwaki Formation

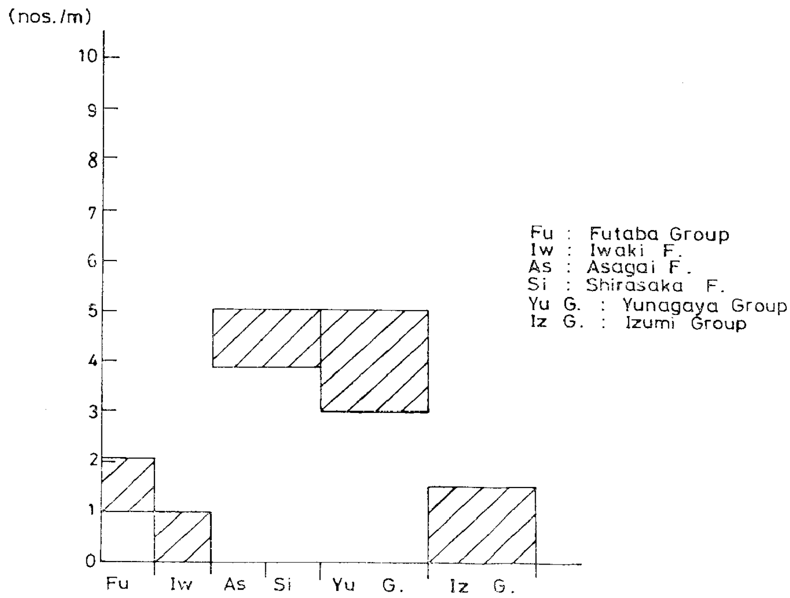


Fig. 27. Mean density of joints in the Futaba and Tomioka Areas

which is composed mainly of conglomerate and conglomerate-bearing coarse grained sandstone. In the fine grained sandstone of the Asagai Formation and mudstone of the Shirasaka Formation the mean density ranges from 3.8 to 5.0 and the development of the joints is good. The Mizunoya and Kameno-o formations and the Honya Mudstone Member of the Taira Formation consists of muddy rocks that had been influenced strongly by the movement of the Futaba disturbed zone and the mean density values are 3.0–5.0. In the Izumi Group and the Yamadahama Formation, both composed mainly of tuffaceous mudstone, the mean density value is less than 1.5 and the development of joints is bad. Even in the neighbourhood of the Futaba thrust fault, the mean density values of the Izumi Group and the Yamadahama Formation do not change so much.

4. CONSIDERATION

Based on the results of the mean density values of the joints described in the foregoing section, the following is considered; 1) The mean density of the joints becomes larger in the order of, muddy rocks, fine grained sandstone, coarse grained sandstone and conglomerate-bearing sandstone. 2) Usually the mean density of the joints of muddy rocks in the Iwaki South Area is less than that in the Iwaki North Area. This seems to show that the degree of influences caused by the tectonic movement of pre-Izumi age was smaller in the Iwaki South Area compared with that in the Iwaki North Area. This can also be proved by the state of development of the faults in both areas. 3) In the Futaba and Tomioka areas a large difference is recognized between the mean density of the muddy rocks of the Yunagaya Group and that of the Izumi Group and the Yamadahama Formation. The mean density in the Izumi Group is not very large even near to the Futaba thrust fault. This proves that a large difference exists between the tectonic movements to which the Yunagaya and Izumi groups were subjected.

JOINT SYSTEM IN EACH AREA

In order to observe the state of development of the joints in detail, it is advisable to measure the joints of the different rock materials. Because each formation in the investigated area is classified, on the whole, by the rock facies, it does not contradict to consider that the measurement of the joints of each formation agrees with that of each different kind of rock materials. Accordingly, the joints in each formation are measured in this paper. The statistical method was done in the following order; at each locality the strike and dips of 30 to 50 joint planes were measured, and a distribution diagram was made by plotting the poles perpendicular to the joint planes on the lower hemisphere of the Schmidt equal-area net, and then by drawing the contour lines in the net. The predominant direction of the joints observed are shown for each group in Figs. 28–33.

1. IWAKI NORTH AREA

It was stated that the Iwaki North Area is subdivided into three smaller blocks by the Akai and Shirasaka faults. The blocks are called in this section with the conventional name of block area, and are from the north; North-, Middle-, and South blocks.

1-a. NORTH BLOCK AREA

This block area is situated between the Futatsuya and Akai faults.

The dominant joints in the granitic rocks of the area have faces with N60°E–N60°W strike and dips of 50°–85°N or S, and N30°W-N30°E strike and dips of 50°–85°E or W, whereas those with NE-SW and NW-SE strike are rare. The joints in the Shiramizu Group, that is to say, the Iwaki-, Asagai-and Shirasaka formations are common, the predominant ones have N60°E-N60°W and N20°E-N30°W strike and dip at 65°–90°E or W. The two predominant trends are common with those recorded in the granitic rocks. Joints in the Yunagaya Group, namely, from the Goyasu Formation up to the Misawa Sandstone Member of the Taira Formation are common, and are similar to the Shiramizu Group in general strike and dip, whereas like the granitic rocks the joints with faces of NE-SW and NW-SE strike are rare in the Ishimoriyama Tuff-breccia Member of the Taira Formation. The dominant joints in the Nakayama Formation have faces with N60°E-N80°W strike and dips of 55°–75°N or S, the second dominant ones are N15°-30°E strike and dips of 70°E or W, NE-SW and NW-SE strike, and the predominant trends accord nearly with those in the Yunagaya Group.

As shown by the figures the joints in the Shiramizu and Yunagaya groups and the Nakayama Formation are common, the two predominant trends agree nearly with those in the granitic rocks.

Because the predominant N60°E-N60°W trending joints in granitic rocks are parallel nearly to the Futatsuya, Akai, Ohira and Okura faults, it is inferred that the predominant ones are closely related with the faults and are shear joints formed under the same stress fields as the faults, whereas, because the other predominant N30°E-N30°W joints are normal nearly to the N60°W-N60°E joints, it is considered that the dominant joints are tension joints.

The dominant N60°E-N60°W trending joints, which are common throughout the Shiramizu and Yunagaya groups and the Nakayama Formation, have trends parallel to the Ohira-, Okura-, Mizushina-, Nagi- and Niitagawa faults, therefore those joints are shear joints formed under the same stress fields as the above faults, in which σ_3, the maximum compressive principal stress, lies with high angle towards the east or west and σ_1, the minimum compressive principal stress, acts with horizontal to low angle towards the north or south. The other dominant N30°E-N30°W trending joints are tension joints formed under the stress fields in which σ_1 lies with low angle towards the east or west when σ_3 was released after the formation of N60°E-N60°W joints, because N30°E-N30°W trends are perpendicular to N60°E-N60°W.

Fig. 28. Joint pattern in the Basement Rocks

Fig. 29. Joint pattern in the Shiramizu Group

Fig. 30. Joint pattern in the Yunagaya Group

Fig. 31. Joint pattern in the Nakayama Formation

1-b. MIDDLE BLOCK AREA

This block area is situated between the Akai and Shirasaka faults.

In the basement rocks composed of granitic and metamorphic rocks, the predominant joints strike N30°E-N30°W with dip of 70°–85°E or W, and strike N60°E-N65°W with dip of 50°–85°N or S, whereas those with NE-SW strike are rare. In the Shiramizu Group the most dominant joints strike N50°E-N50°W (dips 70°–90°N or S) and N30°E–N30°W (dips 60°–90°E or W). The dominant ones of second rank strike NE-SW and NW-SE. Because the tendencies of their strikes agree with those in the basement rocks, it is inferred that the joints distributed in the Shiramizu Group were formed at the time of the movement of the basement blocks. In the Yunagaya Group the joints extending from the Goyasu up to the Misawa Sandstone Member of the Taira Formation are common, and the most predominant trends are N60°E-N60°W (dips 60°–85°N or S) and N30°E–N30°W (dips 65°–85°E or W) and the dominant ones of second rank have SE-NW strike, whereas those with NW-SE strike are rare. These tendencies in trend accord with the ones in the Shiramizu Group, and therefore the joints in the Yunagaya Group were formed by the

Fig. 32. Joint pattern in the Takaku Group

same movement. The most dominant joints in the Nakayama Formation strike N50°E–N50°W (dips 60°–90°N or S) and N30°E-N30°W (dips 60°–90°E or W), and the next dominant ones strike NW-SE and dip 50°–80°N or S, whereas ones with NE-SW strike are rare. Because these trends agree with those in the Yunagaya Group, the joints are inferred to have been formed in the same way as those in the older formations. In the Takaku Group the joints are common in the rocks ranging from the Kamitakaku up to and including the Shimotakaku and those with N60°E-N60°W (dips 60°–90°N or S) and N30°E-N30°W (dips 60°–90°E or W) strikes are most predominant, whereas those with NW-SE strike are dominant in the Shimotakaku Formation. These tendencies accord with the joints in the Nakayama Formation, therefore the joints in this group were made by the same movements the older units were subjected to.

Thus, because joints in the basement rocks and in the Tertiary sedimentary rocks are common, it is considered that the joints distributed throughout the latter rocks were produced as the result of the movement of the basement blocks.

The predominant joints with N60°W to E-W strike in the Tertiary sedimentary rocks are nearly parallel to the trends of the Akai-, Yamazaki, Tatsusawa, Numanouchi,

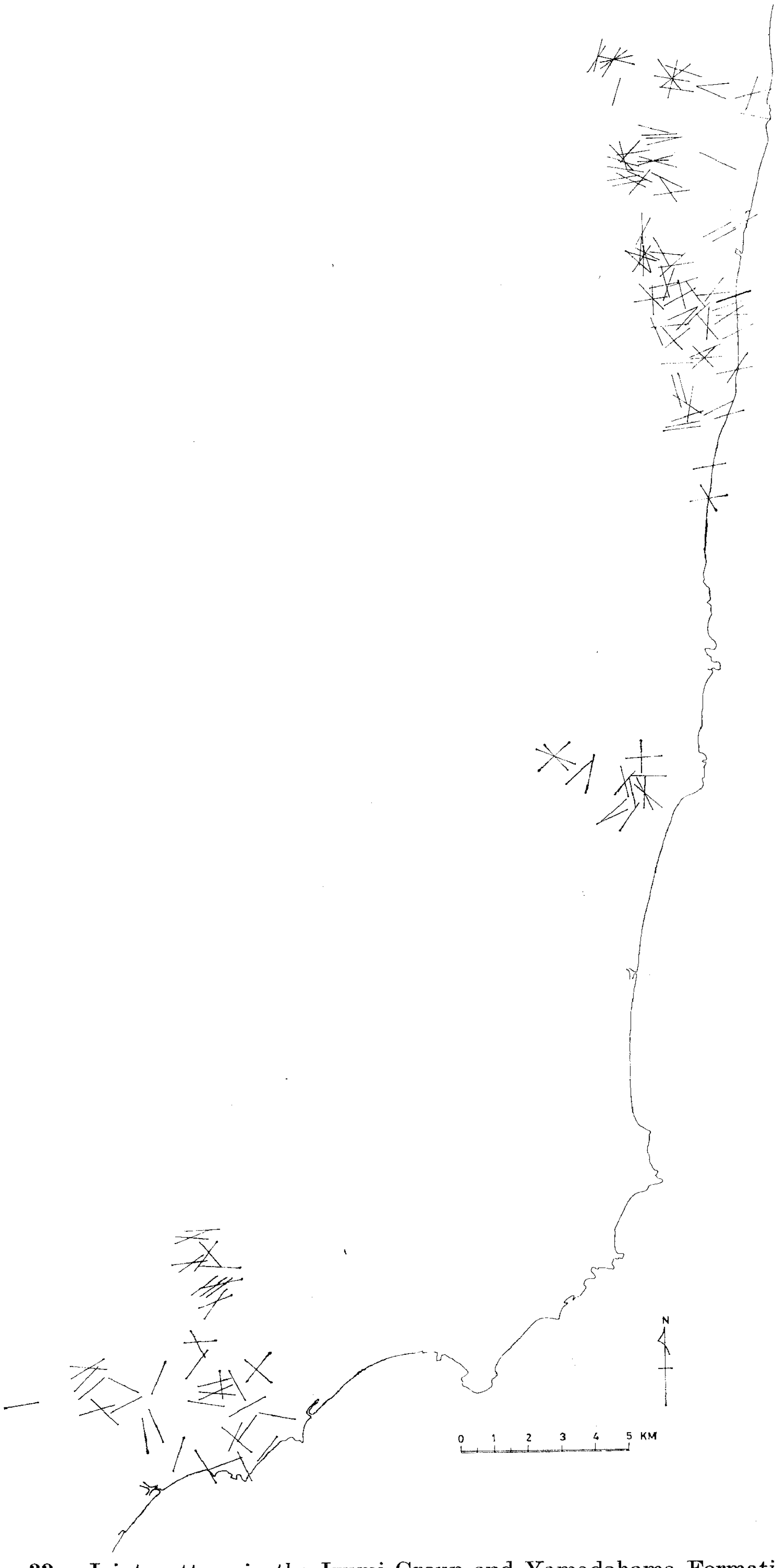


Fig. 33. Joint pattern in the Izumi Group and Yamadahama Formation

Shimizu- and Shirasaka faults. Accordingly, it is thought that the joints are shear joints and were formed under the same stress fields as the above faults, in which σ_3, the maximum compressive principal stress, is with high angle towards the east or west. It is thought that the predominant joints with N60°E to E-W strike are shear joints which make conjugate sets with joints with N60°W to E-W strike, because the angle between both joints is less than 60 degrees. Therefore, the joints with N60°E to N60°W strike are shear joints formed by the same stress fields as the main faults in this block area.

The other predominant joints with N-S to N30°E strike are tension joints, because the joints are nearly parallel to the Yumoto fault set which strikes N5°-30°E and has tension fractures. Joints with N-S to N30°W strike are also tension joints.

1-c. SOUTH BLOCK AREA

Joints in the Shiramizu Group are common in the rocks ranging from the Iwaki Formation through the Shirasaka Formation. The predominant joints strike N35°E-N35°W (dips 70°–90°E or W) and N50°E-N55°W (dips 60°–85°N or S). In the Yunagaya Group the joints are common from the Goyasu Formation up to and including the Misawa Sandstone Member of the Taira Formation. The dominant trends are N50°E-N55°W (dips 60°–90°N or S) and N30°E-N30°W (dips 60°–90°E or W), and this tendency agrees nearly with those of the Shiramizu Group. In the Nakayama Formation the predominant joints have faces trending N60°E-N60°W (dips 60°–85°N or S) and N30°E-N30°W (dips 60°–90°E or W), and this trend accords nearly with those in the Yunagaya Group. In the Takaku Group the joints are common in the rocks from the Kamitakaku up to and including the Shimotakaku. The most dominant joints strike N60°E-N60°W and dip at 60°–85°N or S, and the those with are next important N30°E-N30°W strike and 60°–85°E or W dip. This trend agrees with those in the Nakayama Formation.

Thus the joints in the rocks from the Shiramizu Group up to and including the Takaku Group are common, and it is considered that the two predominant joints mentioned above were the result of the movement of the basement blocks, because the two are dominant in the basement rocks.

Joints with N60°E-N60°W strike in the Tertiary sedimentary rocks are shear joints nearly parallel to the trends of the Shirasaka-, Komoda-, Kuramochi-, Ena-, Karasudate-, and Harakida faults, and were probably formed by the same stress fields as the above faults, in which σ_3 lies with high angle towards the east or west. The joints with N-S to N30°W strike parallel to the trends of the Idosawa fault set are shear joints formed by the same stress fields as the Idosawa fault set, in which σ_3 acts with high angle towards the north or south. Joints with N-S to N30°E trends are tension joints perpendicular to the Shirasaka fault set.

2. IWAKI SOUTH AND TAGA AREAS

The predominant joints in the granitic rocks have faces with N55°E-N65°W (dips 50°–75°N or S) and N18°E-N27°W (dips 65°–90°E or W) strikes. The joints with N60°E-N60°W trend are dominant in the metamorphic rocks. In the Shiramizu Group the predominant trend of the joints are WNW-ESE, WSW-ENE (dips 80°–90°N or S) and NNW-SSE (dips 60°W), and because this tendency agrees with those in the basement rocks they were formed by the same movement. Joints in the Yunagaya Group are common, extending from the Kunugidaira Formation up to and include the Honya Mudstone Member of the Taira Formation. The dominant joints have faces with N60°E-N60°W (dips 60°–85°N or S) and N30°E-N30°W (dips 60°–85°E or W) strikes, this trend accords nearly with those in the Shiramizu Group. Therefore the joints in the Yunagaya

Group were formed by the movement to which the Shiramizu Group was subjected. In the Nakayama Formation joints with N60°E-N60°W (dips 65°–85°N or S) and N30°E-N30°W (dips 70°–85°E or W) strike are dominant, whereas those with NE-SW strike are rare. This trend accords with those in the Yunagaya Group. The predominant trend of the joints in the Takaku Group have faces with N50°E-N75°W (dips 60°–85°N or S) and N25°W-N30°E (dips 65°–85°E) strikes, and this tendency agrees nearly with those in the Nakayama Formation and the Takaku Group which were also formed in the same manner as those in the other groups.

The strike of schistosity in the metamorphic rocks are nearly of N-S trend. Schistosity generally develops normal to the direction of compression. Hence the joints with the two dominant trends were formed by the stress fields in which σ_3 acts with high angles towards the east or west, and it is thought that the joints with N18°E-N27°W strike nearly parallel to the Idosawa Fault (N5°–30°W trend) are shear joints, whereas those with N60°E-N60°W strike are tension joints.

It is known that the faults cutting the Tertiary sedimentary rocks were formed by the strong influence of the basement faults of WNW-ESE trend (the Shirasaka Fault Set) compared with those of NNW-SSE direction (the Idosawa Fault Set). In the Tertiary sedimentary rocks, joints with N60°E-N60°W strike are shear joints formed by the same stress fields as the faults, in which σ_3 acts with high angle towards the east or west, because the joints are parallel to the Yamada Fault and the associated minor faults, whereas the joints with N30°E-N30°W trend are tension joints formed by the stress fields in which σ_1 acts with low angle towards the east or west when σ_3 was released after the formation of the shear fractures of N60°E-N60°W strike.

On the other hand, the dominant trend of the joints in the Izumi Group have faces with N60°E-N60°W (dips 60°–85°N or S) and N30°E-N30°W (dips 60°–85°E or W) strike and are tension joints. There two predominant trends agree with those in the Takaku Group, Nakayama Formation and Yunagaya Group. Therefore, the joints in the Izumi Group were formed by the basement block movement.

3. FUTABA AND TOMIOKA AREAS

Detailed discussion on the joints distributed in these areas will be reserved for another opportunity, and in this section only the results will be presented.

Joints in the basement rocks, and in the Futaba-, Shiramizu, and Yunagaya groups are common, and their predominant trends have faces with strikes of WNW-ESE to WSW-ENE and NNW-SSE to NNE-SSW. This tendency is recognized in the Izumi Group and the Yamadahama Formation.

The dominant joints with NNW-SSE to NNE-SSW strike in the Yunagaya and Izumi groups are closely related to the Futaba thrust fault, they were probably formed by the same stress as the thrust fault. It is considered that the above two dominant joints in the Futaba and Shiramizu groups and those with WNW-ESE to WSW-ENE strike in the Yunagaya Group were formed by the structural control of the basement rocks. All dominant joints in the Izumi Group and the Yamadahama Formation in this area are tension joints.

4. SUMMARY

The joints distributed in the investigated area are characterized as follows; 1) They are common in the rocks of Shiramizu-, Yunagaya-, and Takaku groups and the Nakayama Formation, and the dominant ones have faces with N60°E-N60°W and N30°E-N30°W strike, whereas those with NE-SW and NW-SE strike are rare. This tendency is recognized in the Izumi Group and the Yamadahama Formation. Thus the joints in the investigated area were formed, similar to the faults, by the structural control of the basement rocks. 2) As observed especially in the Iwaki North and Iwaki South areas, it is considered that the dominant joints with N60°E-N60°W trend in each group from the Shiramizu through the Takaku are shear joints formed by the same stress fields as the after mentioned three faults sets, in which σ_3 lies with high angle towards the east or west, because the joints are nearly parallel to the Harakida-, Shirasaka- and Karasudate fault sets. As observed in the stress field of No. T-19, the axes of the principal stress analysed from the conjugate joints with about E-W strike agree nearly with those of the conjugate minor faults having the same trends. 3) The dominant trend of the joints with N-S to N30°E strike in each group from the Shiramizu through the Takaku are perpendicular to the Shirasaka and Harakida fault sets and are parallel to the Yumoto fault set. Hence, these joints were formed by the stress fields similar to the Yumoto fault set, in which σ_1 lies at the maximum with low angle towards the east or west when σ_3, acting with high angle towards the east or west, was released after the formation of the Shirasaka and Harakida fault sets. Therefore, joints with N-S to N30°E strike are tension joints. The dominant joints with N-S to N30°W have characters of shear- and tension joints. 4) Joints in the pre-Izumi Group have the characters of both shear- and tension joints. On the contrary, all of the joints in the Izumi Group are only tension joints. Accordingly, there is a difference of the stress fields, when the joints were formed, between the pre-Izumi Group and the Izumi Group. This proves that there is a difference in the tectonic movement between the Takaku Group and the Izumi Group.

TRI-AXIAL COMPRESSION TEST

As already described based on the field evidence, it became clear that most of the faults and joints that cut the Tertiary sedimentary rocks in the area investigated were formed by the vertical tectonic movements before the deposition of the Izumi Group and by the structural control of the basement rocks after development of the folding structures. Therefore, it is necessary now to examine the origin of the faults and joints, which cut the Tertiary rocks in the present area, from the standpoint of rock mechanics on the basis of the field evidence.

Since about 10 years ago, experimental works on the deformation of rocks under high confining pressure were made by many workers; Griggs (1940), Robertson (1955), Handin and Hager (1957, 1958), Patterson (1958), Heard (1960), Bong and Handin (1966), Patterson and Weiss (1966), Harn, *et al.*, (1967), Scholz (1968, a, b), Mogi (1964, 1965, 1967, 1969), Hoshino (1966, 1967), Yamaguchi (1966), Kobayashi (1966), Masuda (1966), Nagumo (1966), Hara (1967) and Iwamura (1969). For the purpose, mentioned above experiments under high confining pressure were undertaken for the rocks of this region by the present author.

I. SAMPLE AND EXPERIMENTAL METHOD

A series of high pressure tests mainly on the Tertiary sedimentary rocks in the Joban coal-field was undertaken to determine the origin of the faults and joints. For the rock samples, 12 specimens of the Tertiary sedimentary rocks (sandstone, 6 specimens; mudstone, 6 specimens), 2 specimens of granitic rocks, one specimen each of rhyolite and amphibolite were chosen. The sandstone samples were collected from the Iwaki-, Asagai-, Nakayama- and Numanouchi formations and the Izumi Group, and the mudstone samples from the Shirasaka-, Mizunoya-, and Shimotakaku formations and the Honya Mudstone Member of the Taira Formation.

Each sample used for the experiment was made into cylinder shape of 19.5 mm in and 39.0 mm in diameter and in length respectively, after the opinion of Yamaguchi (1966). Each specimen was homogeneous and free from fracture. The cylindrical sample had the long axis perpendicular to the bedding plane, because it is considered that most of the faults in the present area were formed under the stress field in which the maximum compressive principal stress lay acted vertically. The experiments were done on dry samples by the tri-axial compression apparatus of the Geological Survey of Japan. All of the experiments were by the compression test at room temperature (20°–24°C) and under the strain rate of 3.5×10^{-5}/sec.

II. CONSIDERATION

The terms and definitions used were according to Hoshino's report (1966).

Fig. 34 shows that in sandstone and in muddy rocks (Fig. 35) as the confining pressure increases, the strength increases. When the relationship between the strength and the age is considered, it is recognized in sandstone that the strength increases in direct

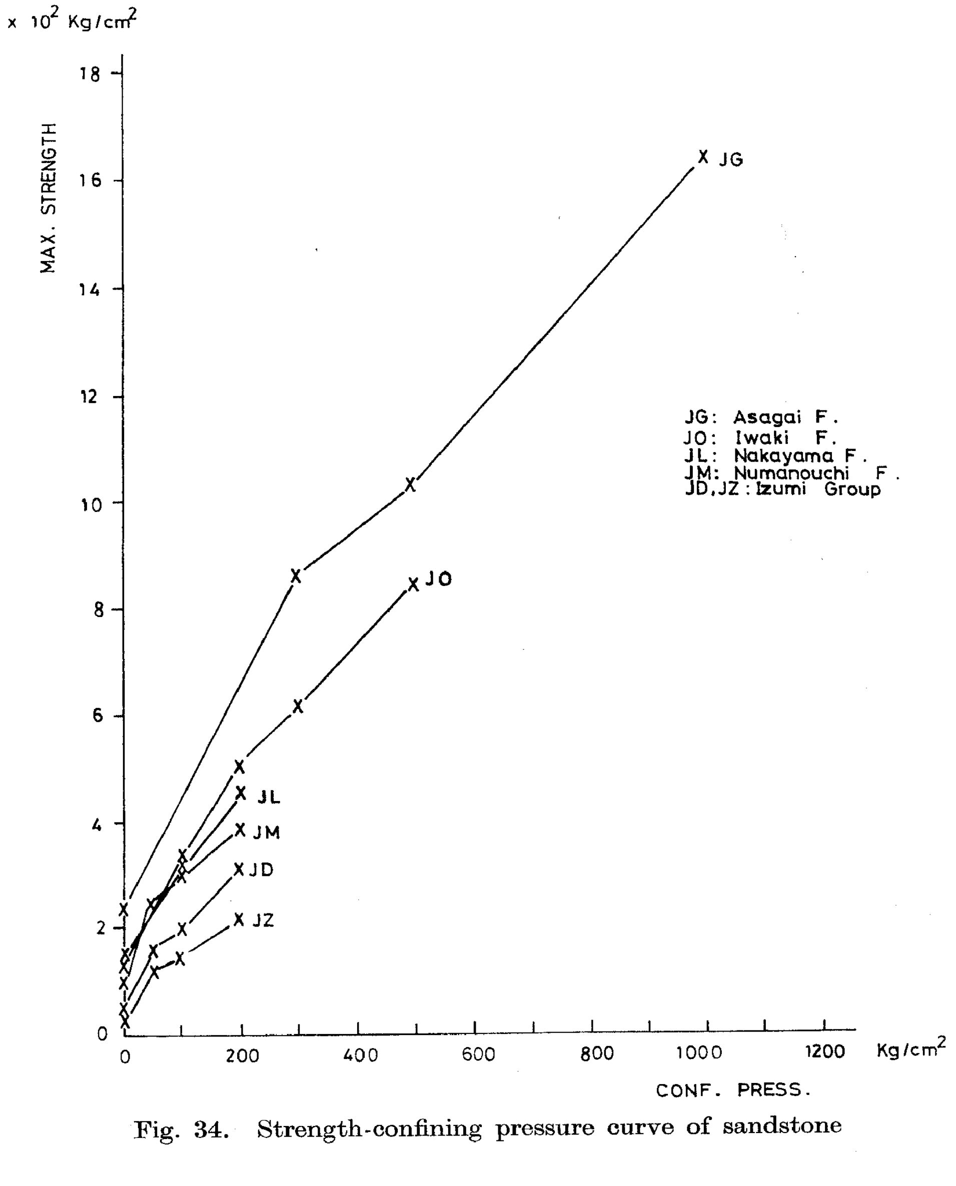


Fig. 34. Strength-confining pressure curve of sandstone

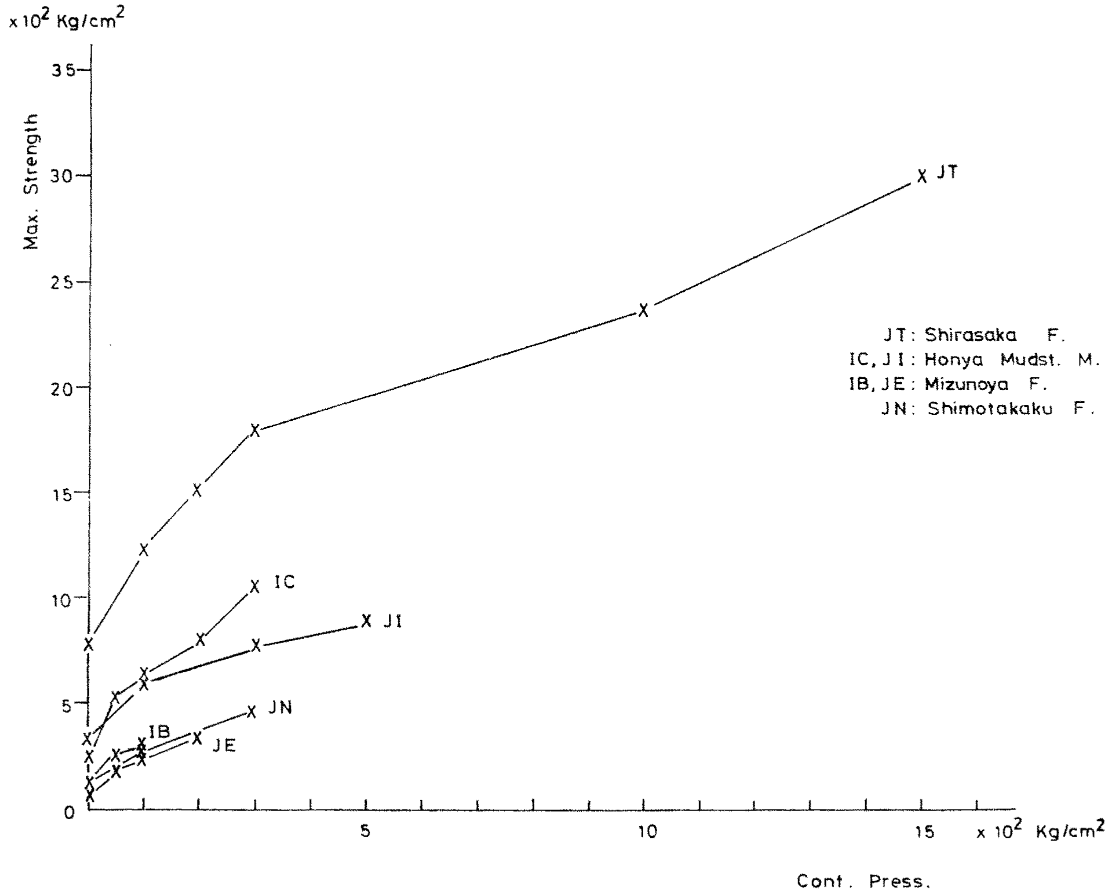


Fig. 35. Strength-confining pressure curve of mudstone

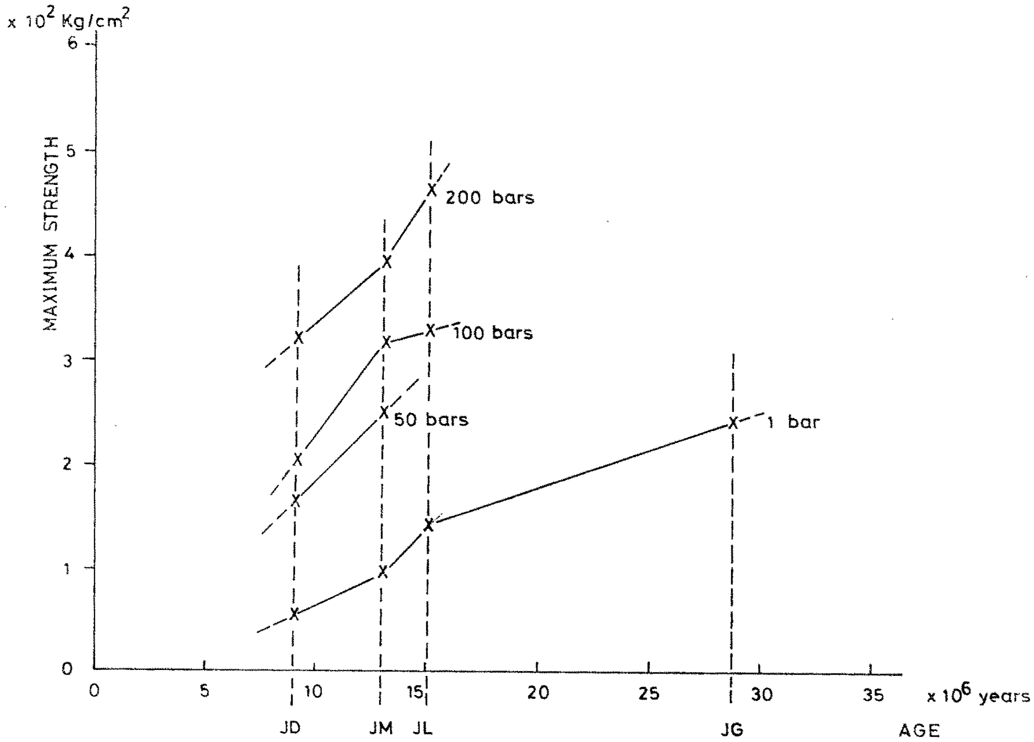


Fig. 36. Strength-age curve of sandstone

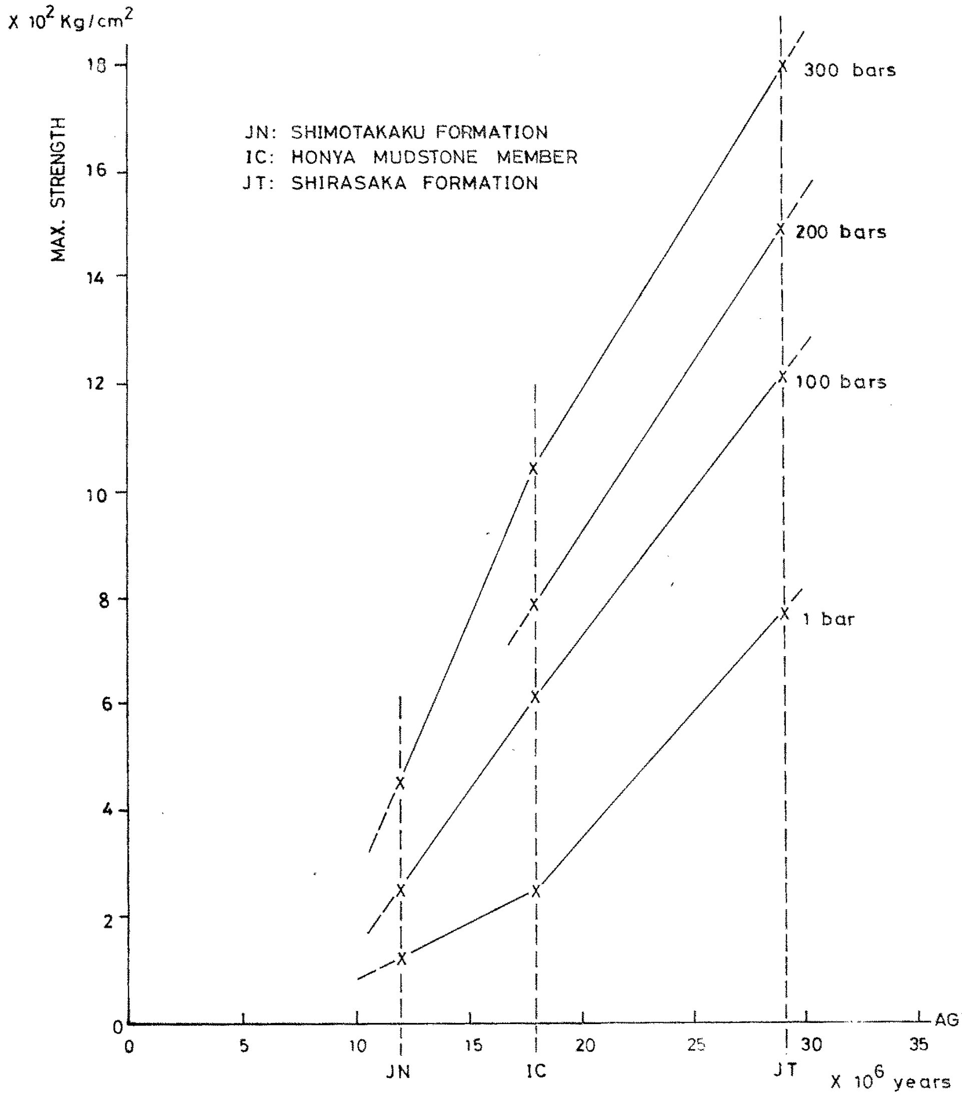


Fig. 37. Strength-age curve of mudstone

proportion to age (Fig. 36), and this tendency is also evident in muddy rocks (Fig. 37). The chronology is tentative according to Chinzei's report (1967). The foregoing facts prove that the strength increases, the deeper the stratum is situated and the older the age is, and these results agree with those of Handin and Hager (1957) and Hoshino (1967). The strength in the muddy rocks of the Mizunoya Formation is smaller than that of the Honya Mudstone Member. This is inferred to be due to that the latter (shaly mudstone) is more compact in comparison with the former (mudstone), even though there is little difference in their ages.

As shown in Fig. 38, plotted after the data of Hoshino (1967), it is evident that the strength in the shaly mudstone of the Shirasaka Formation (Oligocene) is smaller than that of the Tokuman Formation (Oligocene) of the Nishisonogi Group, Oshima Island, Nagasaki Prefecture. The strength of the Honya Mudstone Member correlated with the Funakawa Formation (Miocene), Oga Peninsula, Akita Prefecture is smaller than that of the Miocene Nishiyama Formation of Niigata Prefecture (correlated with the Miocene

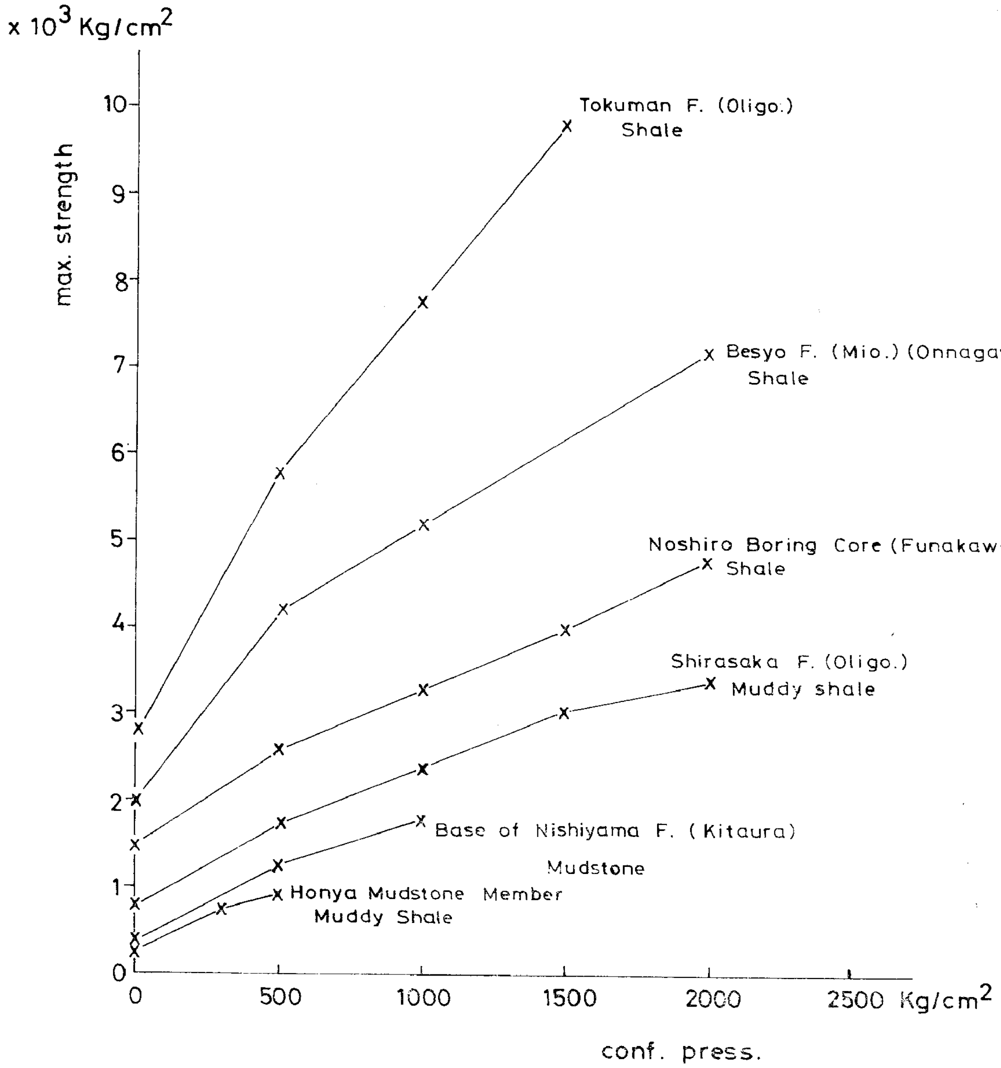


Fig. 38. Strength-confining pressure curve of mudstones in Japan

Kitaura Formation, Oga Peninsula, Akita Prefecture). The strength of the sandstone of the Asagai Formation (Oligocene) is smaller than that of the Mase Formation (Oligocene), Oshima Island (Fig. 39, plotted after the data of Hoshino (1967)), although their ages are similar. Thus, there is a difference in strength for different regions, even in the same rock materials of the same age. The cause for the difference in strength of the rocks seems to be explained by the difference in tectonic history and diagenesis.

As already described among the Joban Tertiary sedimentary rocks, the muddy rocks are more brittle, and the sandstone and tuff more ductile. Fig. 40 shows that the sandstone of the Asagai Formation is more ductile than the mudstone of the Shirasaka Formation; this accords well with the field evidence. Fig. 35 shows that, for muddy rocks of the Mizunoya Formation and the Honya Mudstone Member, their strength in the Iwaki North Area (IC and IB) is larger than those in the Futaba Area (JI and JE).

As indicated in Figs. 41 and 42, the granitic rock and amphibolite of the basement show deformation of brittle rock even at 1,500 bars in confining pressure and make a single shear fracture.

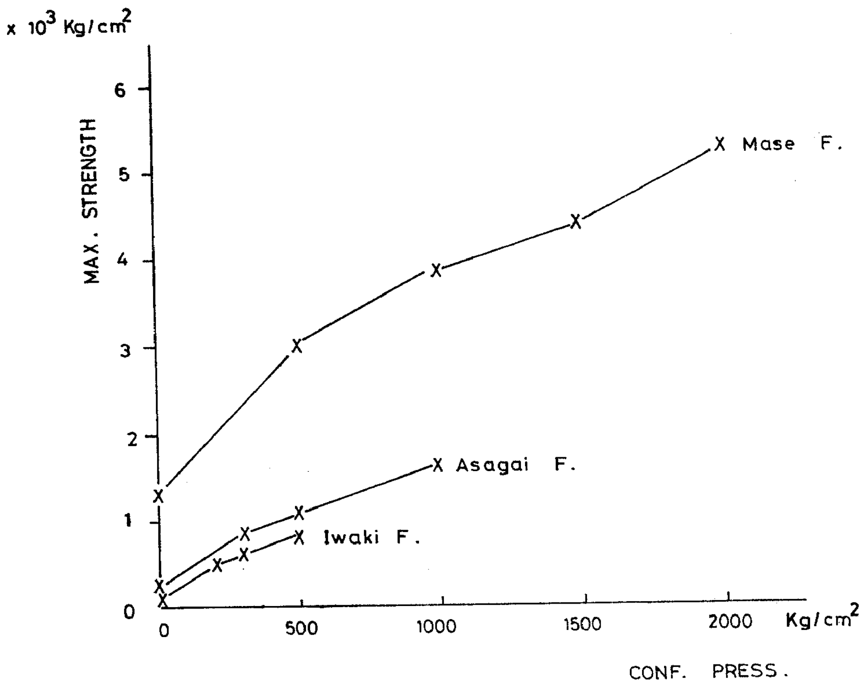


Fig. 39. Strength-confining pressure curve of Oligocene sandstones in Japan

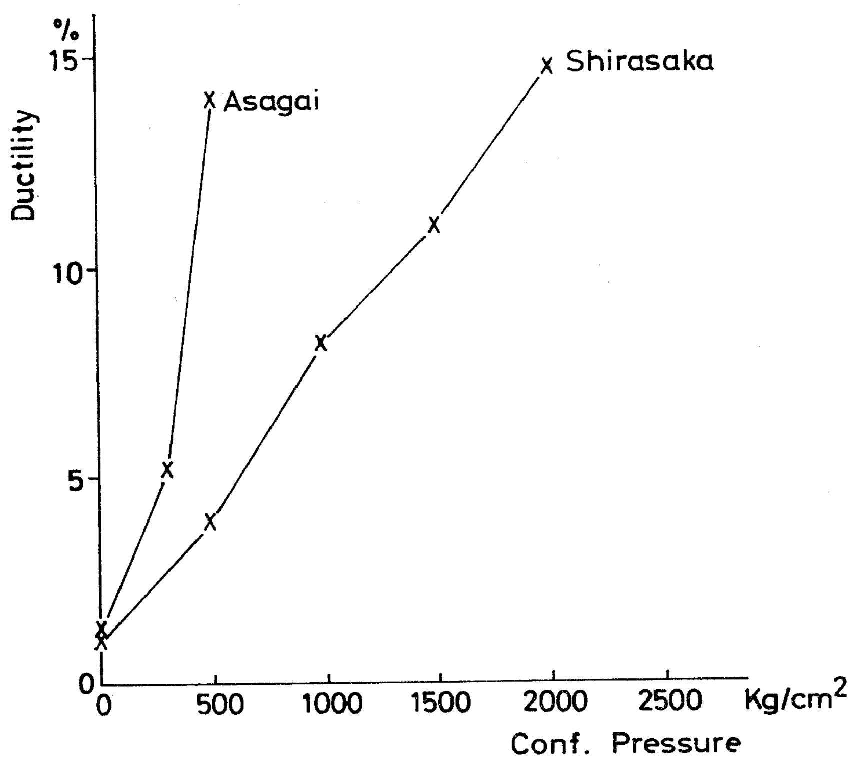


Fig. 40. Confining pressure-ductility curve

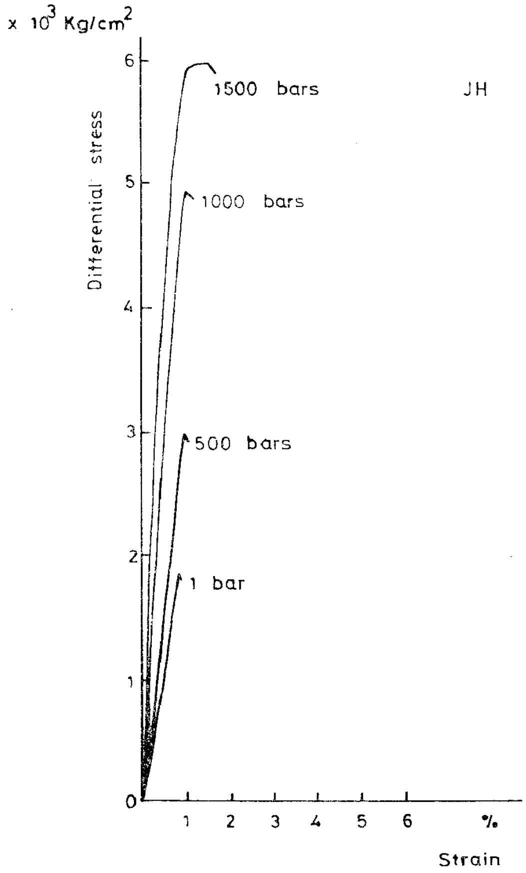


Fig. 41. Stress-strain curve of amphibolite (JH)

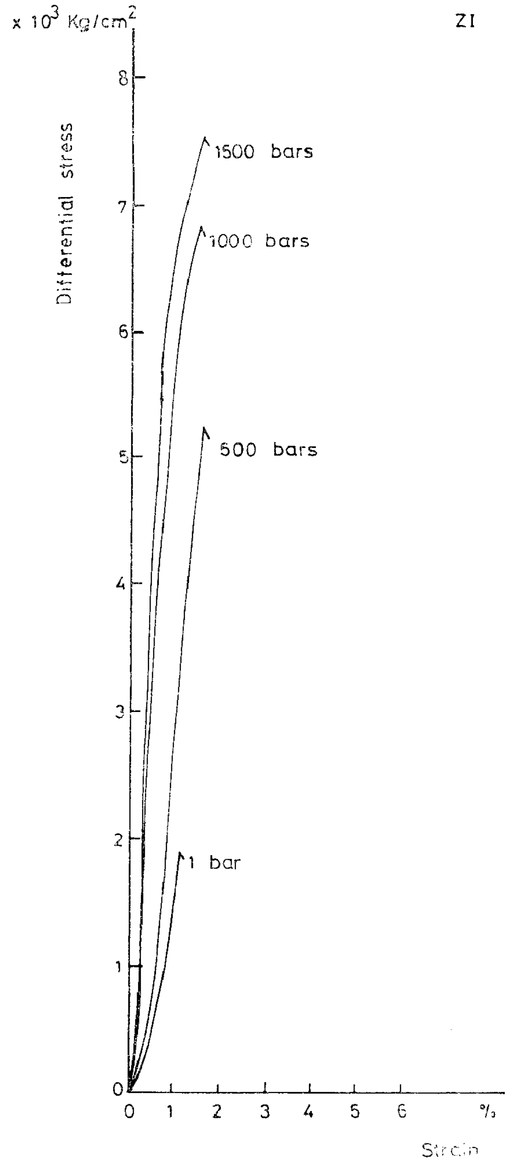


Fig. 42. Stress-strain curve of granite (ZI)

This points to that faults can develop at a depth of 20 kilometers for both types of rocks.

Whereas, in case of the Tertiary sedimentary rocks, for example, the mudstone (IC) of the Honya Mudstone Member shows brittle deformation and makes a single shear fracture under 100 bars in confining pressure, the transitional deformation and a conjugate fracture at 200 bars, and the transitional deformation and no fractures, namely, flow at 300 bars (Figs. 43–44). Shaly mudstone (JT) of the Shirasaka Formation shows brittle deformation and makes a single fracture below 300 bars, the transitional deformation and the single shear fracture at 500 to 800 bars, the transitional deformation and a conjugate fracture at 1,000 bars, and the transitional to ductile deformation and no fractures, namely, flow. Therefore, to bring about a condition for the development of the faults and joints, the muddy rocks should be subjected to 200 bars in confining pressure for the Honya Mudstone Member and to 1,000 bars for the Shirasaka Formation (Fig. 45).

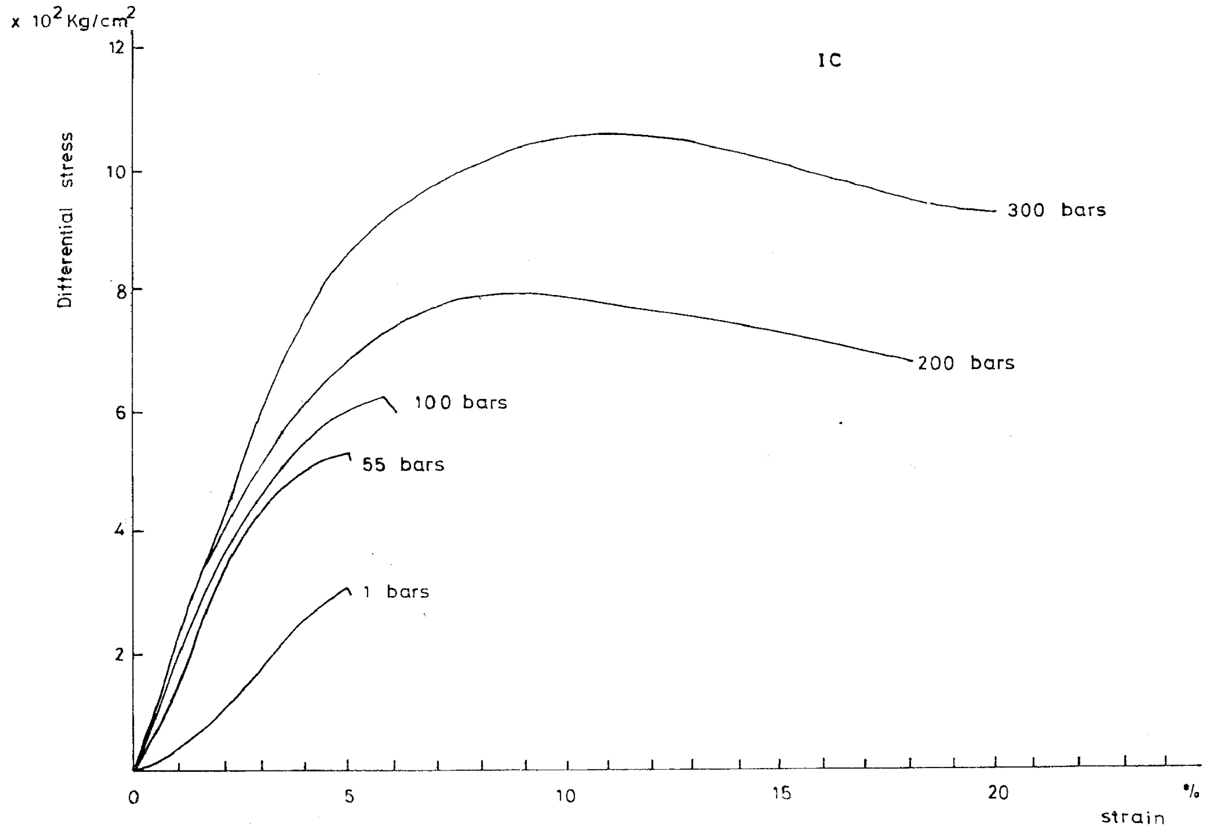


Fig. 43. Stress-strain curve of mudstone of the Honya Mudstone Member (IC)

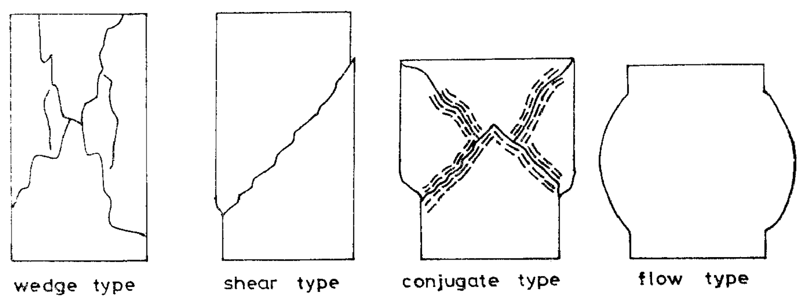


Fig. 44. Typical mode of fracturing

According to Handin *et al.* (1963), σ_3, the lithostatic pressure (overburden pressure), increases at the rate of 230 bars/Km. Namely, σ_z =0.23 h (σ_z; Kg/cm^2, h; depth in meter). Many joints are developed in the Honya Mudstone Member. Also, the faults cutting the member are found, especially in the Onahma district of the Iwaki North Area. For the development of the faults and joints in the Honya Mudstone Member, the mudstone of the member should be subjected to 200 bars, the confining pressure of about or more than that subjected to stress corresponding to about 870 meters in depth. The depth of 870 meters from the surface is equal to the thickness from the middle part of the Honya Mudstone Member to the uppermost part of the Shimotakaku Formation. Therefore, it can be stated that the faults and joints were formed when the mudstone of the Honya Mudstone Member was subjected to a confining pressure equal to about 870 meters depth

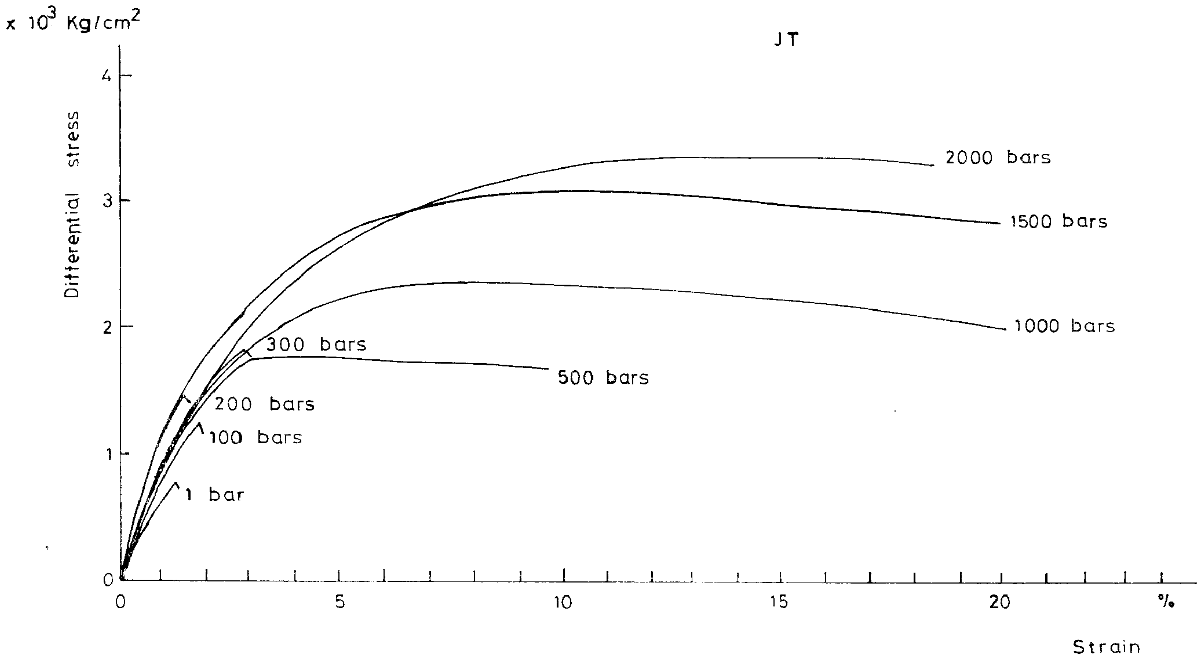


Fig. 45. Stress-strain curve of shaly mudstone of the Shirasaka Formation (JT)

or such a stratal thickness after the development of the fold structures in the investigated area, but was subsequently eroded to the present day condition. This shows that the faults and joints cutting the Tertiary sedimentary rocks in the investigated area were formed after development of the fold structures and at a position not so deep, at about 870 meters below the surface.

Thus, the experiments under high confining pressure can explain at what depth the faults were formed. Hence, the experiments conducted are very useful to solve the condition necessary for the development of the geological structures.

SUMMARY

The results of the present study can be summarized as follows;

1. The investigated area was divided into three sedimentation areas of the Futaba, Iwaki North and Iwaki South areas, and these were developed prior to the deposition of the Iwaki Formation. It is noteworthy that each area makes its own structural unit and each one was subjected to the influence of the respective sedimentary rocks from the Iwaki up to through the Takaku. It is thought that the Futatsuya and Yunotake faults were responsible for separating the investigated area into the three smaller sedimentation areas mentioned already.

2. Up to this time, it had been considered that the stratigraphic relation between the Kunugidaira Formation (Taki coal-bearing Formation) and the Goyasu Formation is a conformity. But, the results of the present studies shows that the relation between them is a partial unconformity as described in the section on stratigraphy.

3. The Takaku Group is superposed by the Izumi Group with unconformity, and the folds and faults were formed by tectonic movement which occurred during post-Takaku Group and pre-Izumi time.

4. The faults that were developed prior to the sedimentation of the Shiramizu Group are the ones with NNW-SSE strike parallel to the Futaba thrust fault and the

Tanakura sheared zone bordering the eastern and western margins of the Abukuma massif respectively, and the faults with WNW-ESE strike parallel to the Futatsuya and Yunotake faults. From the patterns and characteristics features of these structures, it is considered that the old faults of these two sets of faults made a double rhombic structure.

5. Most of the faults can be classified into the Harakida (E-W strike), Idosawa (NNW-SSE strike), Tabasaka (NW-SE strike), Shirasaka (WNW-ESE strike), Karasudate (ENE-WSW strike) and Yumoto (N-SN to NE-SSW strike) fault sets according to the strike of the fault plane, and it is inferred that the faults cutting the Tertiary sedimentary rocks were formed under the strong influence of the faults with WNW-ESE strike pre-existing in the basement.

6. The joints in the basement rocks, Shiramizu-, Yunagaya- and Takaku groups and the Nakayama Formation are common, and the dominant ones have faces with N60°E-N60°W and N30°E-N30°W strikes, whereas those with NE-SW and NW-SE strike are rare. This tendency is recognized in the Izumi Group and the Yamadahama Formation. Thus it is considered that the joints in the investigated area were formed, analogous to the faults due to structural control of the basement.

7. Among the stress fields analysed from the minor faults, the one in which σ_3, the maximum compressive principal axis, lies with high angle towards the east or west was the main and primary one, whereas the other one in which σ_3 lies with high angle towards the north or south was secondary. Therefore, the faults with about E-W strike were formed dominantly in comparison with those of about N-S strike in the Tertiary rocks. Furthermore, it is easily understood that most of the faults are gravity faults from the analysed stress field. The maximum compressive principal stress acting vertically to the surface was due to the vertical tectonic movement.

8. The tri-axial compression experiment pointed to that the faults in the granite and amphibolite of the basement rocks could occur at a depth of 20 km. Also it became clear that the faults and joints in the Honya Mudstone Member were formed when the mudstone of the member was subjected to a confining pressure corresponding to about 870 meters depth or such a thickness of the superposed strata was attained due to erosion after the development of the fold structure and uplift in the investigated area, but was further eroded to the present day condition. This consideration suggests that the faults cutting the Tertiary sedimentary rocks in the investigated area were formed after development of the fold structures and at a position not so deep below the surface.

REFERENCES

Asano, K., 1949, Foraminifera from the Asagai Formation (Tertiary) of Fukushima Prefecture, Japan. *Jour. Paleont.*, v. 23, no. 5, p. 473–478, 2 text-figs.

————, and Takayanagi, Y., 1965, Stratigraphic significance of planktonic Foraminifera from Japan. *Tohoku Univ., Sci. Rep., 2nd. Ser. (Geol.)*, v. 37, no. 1, p. 1–14, 2 figs., 5 tables.

Bong, I. and Handin, J., 1966, Experimental deformation of crystalline rocks. *Tectonophysics*, v. 3, no. 4, p. 249–368., 42 figs., 10 tables.

Chinzei, K., 1967, An attempt for absolute chronology of Neogene in Japan by biostratigraphic correlation. *Geol. Soc. Japan, Jour.*, v. 73, no. 4, p. 220–221, 2 figs. (in Japanese)

de Sitter, 1956, Structural Geology. *McGraw-Hill Inc., London*, 552 pp.

Eguchi, M. and Suzuki, S., 1953, A study of the coal sedimentation in the Joban Coal Field. (3), Subsurface structure of the southern margin of the Joban Coal Field. *Jour., Jap. Min. Petro. Econ. Geol.*, v. 37, no. 2, p. 65–75, 5 figs. (in Japanese with English abstract)

————, Shoji, R., and Suzuki, S., 1954, Coal sedimentation in the Joban Coal Field (2)-Vicinity of Hirono-machi, Futaba District, Fukushima Prefecture. *Geol. Soc. Japan, Jour.*, v. 59, no. 694, p. 544–551, 2 figs., 1 table. (in Japanese with English abstract)

Exploitation of Natural Gas in Joban District, 1962, v. 1, p. 1–78.

Fujita, Y., Kutsuzawa, A., and Mitsunashi, T., 1965, On planeless fault at the boundary of sedimentary basins, and its genesis, Part 1. *Earth Science* (*Chikyu Kagaku*), no. 76, p. 1–14, 11 figs., 1 table, 1 photo. (in Japanese with English abstract)

Griggs, D., 1940, Experimental flow of rocks under conditions favoring recrystallization. *Geol. Soc. Amer. Bull.*, v. 51, p. 1001–1022, 10 figs., 2 pls.

Hahn, S.J., Ree, T., and Eyring, H., 1967, Mechanism for the plastic deformation of Yule Marble. *Geol. Soc. Amer., Bull.*, v. 78, p. 773–782, 5 figs.

Handin, J., and Hager, R.V.Jr., 1957, Experimental deformation of sedimentary rocks under confining pressure; Tests at room temperature on dry samples. *Amer. Assoc. Petrol. Geol., Bull.*, v. 41, no. 1, p. 1–50, 44 figs., 2 tables.

Handin, J., and Hager, R.V.Jr., 1958, Experimental deformation of sedimentary rocks under confining pressure; Tests at High Temperature. *Amer. Assoc. Petrol. Geol., Bull.*, v. 42, p. 2892–2934, 31 figs., 5 tables.

Handin, J., *et al.*, 1963, Experimental deformation of sedimentary rocks under confining pressure; Pore Pressure Test. *Amer. Assoc. Petrol. Geol., Bull.*, v. 47, no. 5, p. 717–755, 28 figs., 7 tables.

Hanzawa, S., 1954, 1957, Tohoku Region. *Asakura Co., Tokyo*, p. 1–302. (in Japanese)

Hara, L., 1967, A note on "Concentric" folding of multilayered rocks. *Hiroshima Univ., Jour. Sci., Ser. C.*, v. 5, no. 3, p. 217–239, 9 text-figs., 2 tables, 4 pls.

Hatai, K., and Kamada, Y., 1950, Fossil evidence for the geological age of the Uchigo Group, Joban Coal-Field. *Short Papers, Inst. Geol. Pal. Tohoku Univ.*, no. 2, p. 58–73, 1 fig., 3 tables.

Heard, H.C., 1960, Transition from brittle fracture to ductile flow in Solenhohen limestone as a function of temperature, confining pressure, and interstitial fluid pressure. *Geol. Soc. Amer., Mem.* 79, Rock Deformation, p. 196–226.

Hirabayashi, T., 1965, Joint system and fault system of Granites in the west of the Matsumoto Basin, Nagano Prefecture. *Geol. Soc. Japan, Jour.*, v. 71, no. 832, p. 18–31, 9 figs. (in Japanese with English abstract)

Hirano, M., 1969, Joint system of the Rokko mountain range-tectonics of uplifted massif in the Kinki district, Japan (I). *Osaka City Univ., Jour. Geosci.*, v. 12, art. 3, p. 25–44, 13 figs., pl. 1.

Hirayama, K., 1952, On the Yotsukura Formation in the middle part of the Joban coal-field. *Geol. Soc. Japan, Jour.*, v. 58, no. 682, p. 299. (in Japanese)

Hirayama, J., and Kakimi, T., 1965, An analytical method for determination of tectonic stress-field and its application. *Earth Science* (*Chikyu Kagaku*), no. 78, p. 23–31, 15 figs., 1 pl. (in Japanese with English abstract)

Hoshino, K., 1965, Fracture system and natural gas occurrence in the Joban Coal-Field. *Geol. Surv. Japan, Rep.* no. 210, p. 1–36, 19 figs., 3 tables, 4 photos.

————, 1966, Rock deformation and geologic structure. *Geol. Soc. Japan, Jour.*, v. 72, no. 3, p. 105–116, 13 figs., 1 pl. (in Japanese with English abstract)

————, 1967, Mechanical properties of some Japanese sedimentary rocks under confining pressure (1). *Applied Geol.*, v. 8, no. 3, p. 151–164, 15 figs., 4 photos. (in Japanese with English abstract)

————, 1967, Fracture system of Oshima Island, Kyushu; A study of jointing in brittle sedimentary rocks. no. 222, *Geol. Surv. Japan, Rep.* 53 pp., 41 figs., 6 pls. (with German abstract)

Ishiguri, I., 1968, MS, Geology of the Tono-cho district, Iwaki City, Fukushima Prefecture. *Tohoku Univ., Inst. Geol. Paleont., Grad. Thesis.* (MS) (in Japanese)

Iwai, J., 1950, Kameno-o Formation (Tertiary) of the Joban Coal-Field. *Short Papers, Inst. Geol. Pal., Tohoku Univ.*, no. 1, p. 59–77, 1 map.

————, 1953, Intraformational abnormal deposition observed in the Kameno-o Formation. *Tohoku Univ., Inst. Geol. Pal., Contr.*, no. 42, p. 1–22, 16 figs., 3 pls. (in Japanese with English abstract)

Iwamura, S., 1969, Mechanical properties of some Japanese Tertiary sedimentary rocks under confining pressure (3). *Geol. Soc. Japan, Jour.*, v. 75, no. 2, p. 78. (in Japanese)

Iwao, S., and Matsui, H., 1961, Explanatory text of the geological map of Japan, Scale 1:50,000, Taira and Kawamae. *Geol. Surv. Japan.* (in Japanese with English abstract)

Kakimi, T., Hirayama, J., and Kageyama, K., 1966, Tectonic stress-fields deduced from the minor fault system in the Northern part of the Miura Peninsula. *Geol. Soc. Japan, Jour.*, v. 72, no. 10, p. 469–489, 24 figs. (in Japanese with English abstract)

————, 1968, On some problems concerning minor-faults. *Chinetsu*, no. 17, p. 5–13, 9 figs., 2 tables. (in Japanese with English abstract)

Kamada, Y., 1962, Tertiary marine Mollusca from Joban Coal-field, Japan. *Paleont. Soc. Japan, Spec. Pap.*, no. 8, p. 1–187, 3 figs., 2 text-figs., 21 pls.

Kawano, Y., and Ueda, U., 1965, K-A dating on the igneous rocks in Japan — Granitic rocks in Abukuma massif—, *Jap. Assoc. Min. Petrol. Econ. Geol., Jour.*, v. 54, no. 5, p. 162–172, 2 figs., 4 tables. (in Japanese with English abstract)

Kimura, T., 1966, Tectonic movement in the Southern Fossa Magna, Central Japan, analysed by the minor structures in its southwestern area. *Japan. Jour. Geol. Geogr.*, v. 37, no. 1, p. 63–85, 10 figs., 1 table.

————, 1968, Some folded structures and their distribution in Japan. *Japan. Jour. Geol. Geogr.*, v. 39, no. 1, p. 1–26, 12 figs., 2 tables.

Kinugasa, Y., Kakimi, T., and Hirayama, J., 1969, The minor faults system on the coastal area of the eastern Boso Peninsula. *Geol. Surv. Japan, Bull.*, v. 20, no. 1, p.13–38, 20 figs., 3 tables., 8 pls. (in Japanese with English abstract)

Kitamura, N., 1962, Preliminary report on systematic jointing in the Taishu Group developed in Mitsushima-cho, Tsushima Islands, Japan. *Tohoku Univ., Sci. Rep., 2nd. Ser.* (*Geol.*), *Spec. Vol.*, no. 5, p.303–319, 5 text-figs., 2 tables, 50 pls.

————, 1963, Tertiary tectonic movement of the Green Tuff area. *Paleont. Soc. Japan, Fossils*, no. 5, p. 123–137, 6 figs., 1 table. (in Japanese)

Kobayashi, R., 1966, On the shearing strength of the rock materials. *Symposium on the Strength-Tests of Rocks*, p. 18–29, 18 figs., 2 tables. (in Japanese)

Kodama, K., 1968, An analytical study on the minor faults in the Joga-shima Island. *Geol. Soc. Japan, Jour.*, v. 74, no. 5, p. 265–278, 7 figs., 6 tables, 1 pl. (in Japanese with English abstract)

Komatsu, N., and Watanabe, T., 1968, Preliminary report on the stress distribution in Nishiyama oil-field, Niigata Prefecture. *Jap. Assoc. Petrol. Techn., Jour.*, v. 33, no. 3, p. 157–162, 7 figs., 1 table. (in Japanese with English abstract)

Kutsuzawa, A., and Fujita, Y., 1966, Genesis of clastic dikes and planeless deposites of the Sendai district — Studies on faults at the boundary of sedimentary basins (2) —, *Geol. Soc. Japan, Jour.*, v. 73, no. 1, p. 19–34, 7 figs., 4 tables, 3 pls. (in Japanese with English abstract)

Masuda, H., 1966, Exploration of geological structure of Dam site. *Geol. Soc. Japan, Jour.*, v. 72, no. 3, p. 143–159, 20 figs., 6 tables. (in Japanese with English abstract)

Mita, S., 1951, The geology of the northern Futaba district in Joban coal field. *Geol. Surv. Japan, Rep.* no. 140, p. 1–44, 3 figs., 17 tables, 10 pls. (in Japanese with English abstract)

Mitsui, S., 1967, Stratigraphy and geological structure in the middle to north area of the Iwaki City, Fukushima Prefecture. *Tohoku Univ., Inst. Geol. Paleont., Master Thesis* (MS). (in Japanese)

————, 1969, Analysis of minor faults in the area between Taira and Onahama. *Tohoku Univ., Inst. Geol. Pal., Contr.*, no. 67, p. 99–117, 7 figs., 2 tables., 1 pl. (in Japanese with English abstract)

Miyashita, A., 1965, Metamorphic rocks and metamorphic belt. *Iwanami Co., Tokyo*, 458 pp.

Mogi, K., 1964, Deformation and fracture of rocks under confining pressure (1), Compression tests in dry rock sample. *Earthq. Res. Inst., Bull.*, v. 42, p. 491–514.

————, 1965, Deformation and fracture of rocks under confining pressure (2), Elasticity and plasticity of some rocks. *Earthq. Res. Inst., Bull.*, v. 43, p. 349–379, 19 figs.

————, 1967, Earthquake and fractures. *Tectonophysics*, v. 5, no. 1, p. 35–56, 19 figs.

————, 1969, Experiments on the rock fracture — To solve the earthquake phenomena—. *Science* (*Kagaku*), v. 39, no. 2, p. 95–102, 11 figs. (in Japanese)

Murai, I., 1965, The fracture system developed in the vicinity of Katsuura, the Boso Peninsula. *Earthq. Res. Inst., Bull.*, v. 43, no. 4, p. 829–869, 20 figs., 2 tables. (in Japanese with English abstract)

————, 1965, Fracture system developed on the Island, Awa-shima, near the epicenter of the Niigata earthquake in 1964. *Earthq. Res. Inst., Bull.*, v. 43, no. 3, p. 611–624, 19 figs. (in Japanese with English abstract)

———, 1966, Tectonic analysis of the district between Murakami and Tsuruoka. *Geol. Surv. Japan, Spec. Rep.*, no. 3, p. 15–25, 7 figs. (in Japanese with English abstract)

———, 1967, Fracture analysis of the seismic area where the Matsushiro earthquake swarm has been occurring. *Earthq. Res. Inst., Bull.*, v. 45, no. 2, p. 505–536, 20 figs. (in Japanese with English abstract)

Nagumo, S., 1966, Kinematic theories of folding. *Geol. Soc. Japan, Jour.*, v. 72, no. 3, p. 117–130, 14 figs., 6 tables. (in Japanese with English abstract)

Nakamura, S., 1913, Geology of the environs of Yumoto, province of Iwaki. Expl. Detailed Geol. Map Joban Coal Field, Sec. 1. *Imp. Geol. Surv. Japan*, p. 1–14 (in Japanese)

Ninagawa, S., 1954, Seismic prospecting on Tomioka district, Joban Coal Field. *Geol. Surv. Japan, Bull.*, v. 5, no. 9, p. 483–492, 6 figs. (in Japanese with English abstract)

Obata, I., 1967, Note on the upper limit of the Cretaceous Futaba Group. *Geol. Soc. Japan, Jour.*, v. 73, no. 9, p. 443–444. (in Japanese)

———, and Suzuki, T., 1969, Additional note on the upper limit of the Cretaceous Futaba Group. *Geol. Soc. Japan, Jour.*, v. 75, no. 8, p. 443–445, 3 figs. (in Japanese)

Patterson, M.S., 1958, Experimental deformation and faulting in Wombeyan Marble. *Geol. Soc. Amer., Bull.*, v. 69, p. 465–476, 8 figs., 2 pls.

———, and Weiss, L.E., 1966, Experimental deformation and folding in Phyllite. *Geol. Soc. Amer., Bull.*, v. 77, p. 343–374, 20 figs., 9 pls.

Research Group of the Abukuma Plateau, 1969, Polymetamorphism in the Abukuma Plateau with speical regards to the discovery of Staurolite and Kyanite. *Geol. Soc. Japan, Mem.*, no. 4, p. 83–98, 10 figs., 3 tables. (in Japanese with English abstract)

Robertson, E.C., 1955, Experimental study of the strength of rocks. *Geol. Soc. Amer., Bull.*, v. 66, p. 1275–1314.

Saito, T., 1963, Miocene planktonic Foraminifera from Honshu, Japan. *Tohoku Univ., Sci. Rep., 2nd Ser.* (*Geol.*), v, 35, no. 2, p. 123–209, 15 figs., 16 tables, 4 pls.

Scholz, C.H., 1968, Micro fracturing and the inelastic deformation of rock in compression. *Geophys. Res. Jour.*, v. 73, no. 4, p. 1417–1432, 12 figs., 4 tables.

———, 1968, Experimental study of the fracturing process in brittle rock. *Geophys. Res., Jour.*, v. 73, no. 4, p. 1447–1454, 5 figs., 1 table.

Sugai, N., and Matsui, H., 1953, Report on the geology of the eastern part of Yumoto, Iwaki district, Central Part of Joban Coal Field, Fukushima Prefecture. *Geol. Surv. Japan, Rep.*, no. 157, p. 1–58, 11 figs., 8 tables, 2 maps. (in Japanese with English abstract)

———, and ———, 1957, Geological maps of the coal fields of Japan (I), Geological map and Explanatory Text of the Joban Coal Field, Scale 1:50,000. *Geol. Surv. Japan*, 143 pp., 52 figs., 59 tables, 7 pls. (in Japanese with English abstract)

Takai, F., 1961, A new *Anthracothere* from the Shiramizu Group in the Joban Coal-Field, Japan, with notes on its geological age. *Japan Acad., Proc.*, v. 37, no. 5, p. 254–260, 3 figs.

Takayama, T., and Obata, I., 1968, Discovery of *Nannoplanktons* from the upper Cretaceous Futaba Group. *Geol. Soc. Japan, Jour.*, v. 74, no. 3, p. 187–189, 2 figs. (in Japanese)

Tanai, T., 1955, Illustrated catalogue of Tertiary plants in Japanese Coal Field—I. Early and Middle Miocene floras—. *Geol. Surv. Japan, Rep.*, no. 163, p. 1–16, 1 fig., 3 tables, 22 pls., (in Japanese with English abstract)

Tokunaga, S., 1927, Geology of the Joban Coal-Field. *Fac. Sci. Eng., Waseda Univ., Mem.*, no. 5, p. 1–316, 10 pls. (in Japanese)

Tsuneishi, Y., 1966, Geological structure of the Hirono area in the Abukuma mountains. *Earthq. Res. Inst., Bull.*, v. 44, p. 749–764, 20 figs. (in Japanese with English abstract)

Watanabe, 1934, The geology of the environs of Kadono and the Kuroda and Sakura basins, province of Iwaki. Expl. detailed Geol. Map., Joban Coal-Field, Sec. 3, *Imp. Geol. Surv. Japan*, p. 1–106. (in Japanese with English introduction)

Yabe, H., and Aoki, R., 1924, Mesozoic and Cenozoic history of the Abukuma Plateau and its foreland along the Pacific coast. *Japan. Jour. Geol. Geogr.*, v. 3, nos. 3–4, p. 23–27.

Yamaguchi, T., 1965, Tectonic study of rock fractures. *Geol. Soc. Japan, Jour.*, v. 71, no. 837, p. 257–275, 22 figs.

Yamaguchi, U., 1966, On the compressive strength. *Symposium on the Strength-Tests of Rocks*, p. 1–9, 7 figs., 1 table. (in Japanese)

Yanagisawa, I., 1967, Geology and paleontology of the Takakura-Yaguki area, Yotsukura-cho, Fukushima Prefecture. *Tohoku Univ., Sci. Rep., 2nd Ser.* (*Geol.*), v. 39, no. 1, p. 63–112, 4 figs., 3 tables, 6 pls.

Explanation of Plate 27

Fig. 1. Outcrop of a land-slide in the Mizunoya Formation. Locality; Joban west Coal Mine.
Fig. 2. Outcrop of land-slide in the Honya Mudstone Member of the Taira Formation, caused by a fault parallel to the bedding plane. Locality; Ososawa, Taira.
Fig. 3. Outcrop and close view of a part of Fig. 1.
Fig. 4. Outcrop showing the sandstone layers dragged into mudstone layers by joints in the Mizunoya Formation. Locality; Joban-Mizunoya.
Fig. 5. Outcrop of a sandstone dike in the Kunugidaira Formation. Locality; Kami-Yamada, Yamada-cho.

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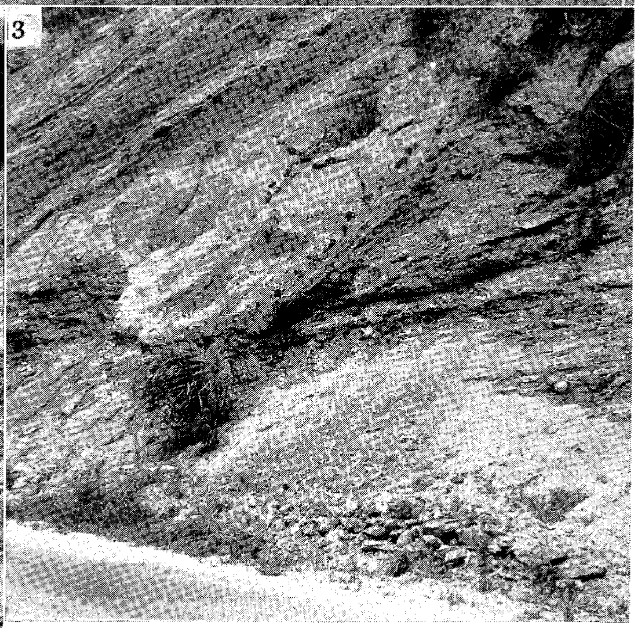

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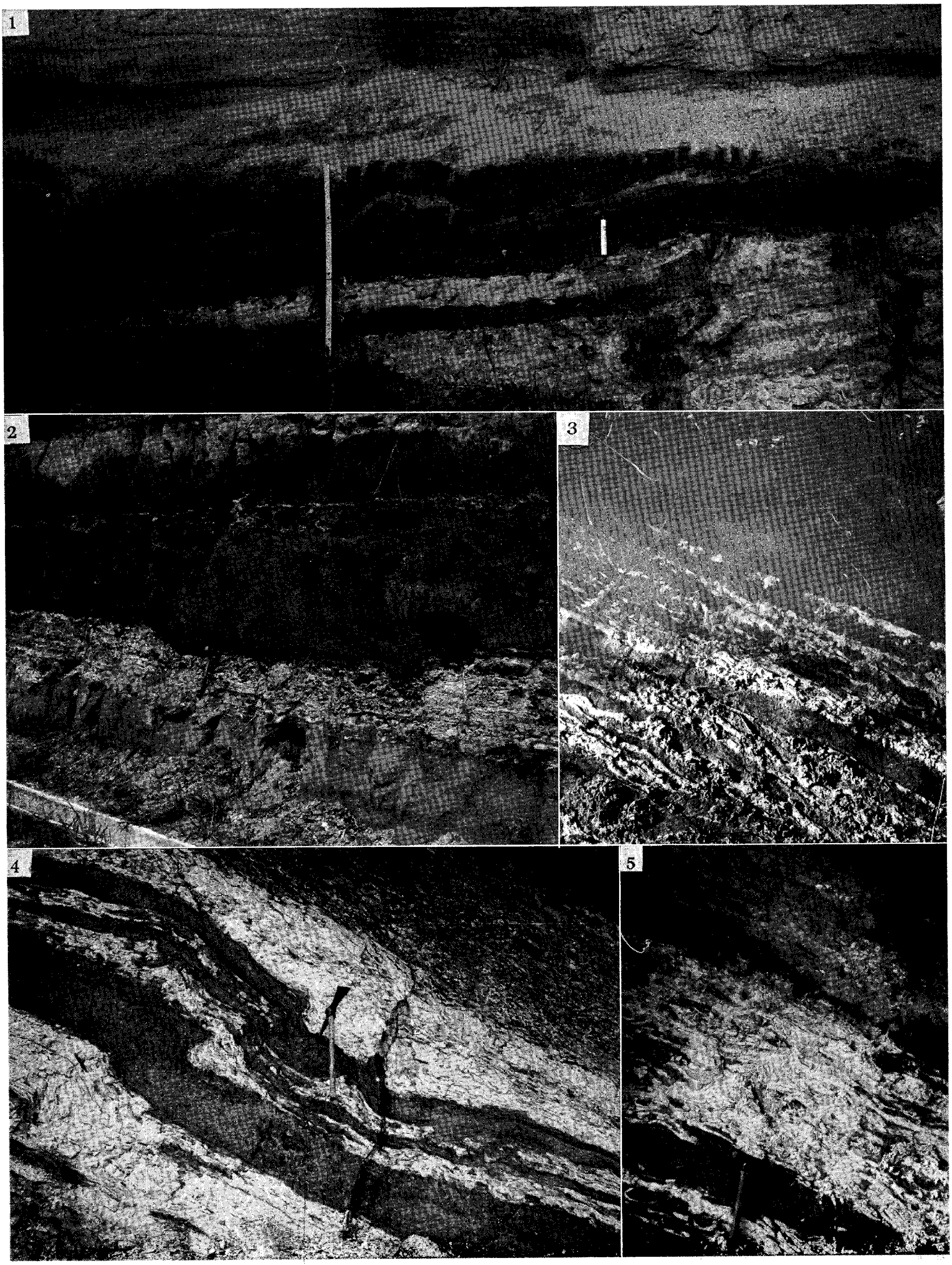
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Explanation of Plate 28

Fig. 1. Close view of the intraformational folding in the Kamiyata Sandstone Member of the Taira Formation. Locality; North of Ebata, Yamada-cho.

Fig. 2. Close view of a load-cast in the Kamiyata Sandstone Member of the Taira Formation. Locality; Izumida, Izumi-cho.

Figs. 3, 4. 5. Close view of the intraformational folding in the Kameno-o Formation. Locality; North of Ebata, Yamada-cho.

Explanation of Plate 29

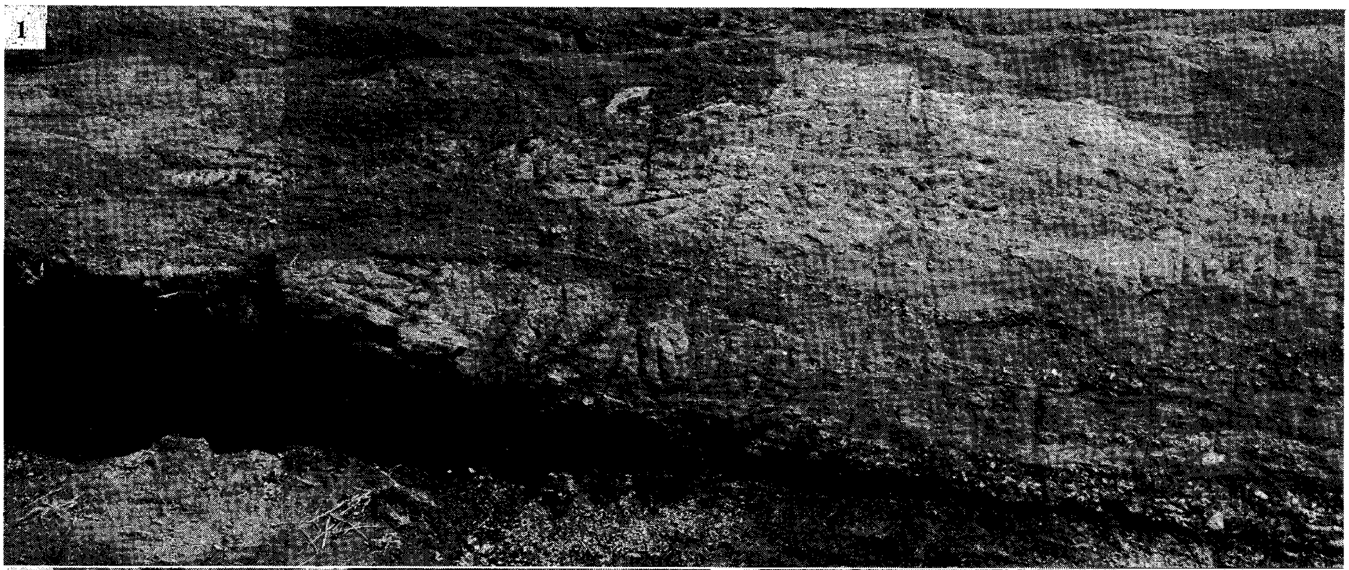
Fig. 1. Outcrop showing the unconformity between the Shirasaka and Goyasu formations. Locality; Shirasaka, Joban-Yumoto-machi. The conglomerate of the Goyasu Formation includes materials derived from the Shirasaka Formation.

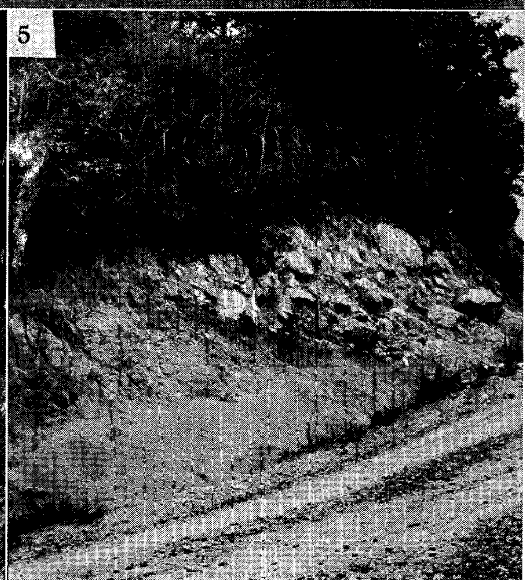
Fig. 2. Outcrop showing the unconformity between the Shirasaka and Goyasu formations. The basal conglomerate of the Goyasu Formation is well developed. Locality; Furudate, Hirakubo, Taira.

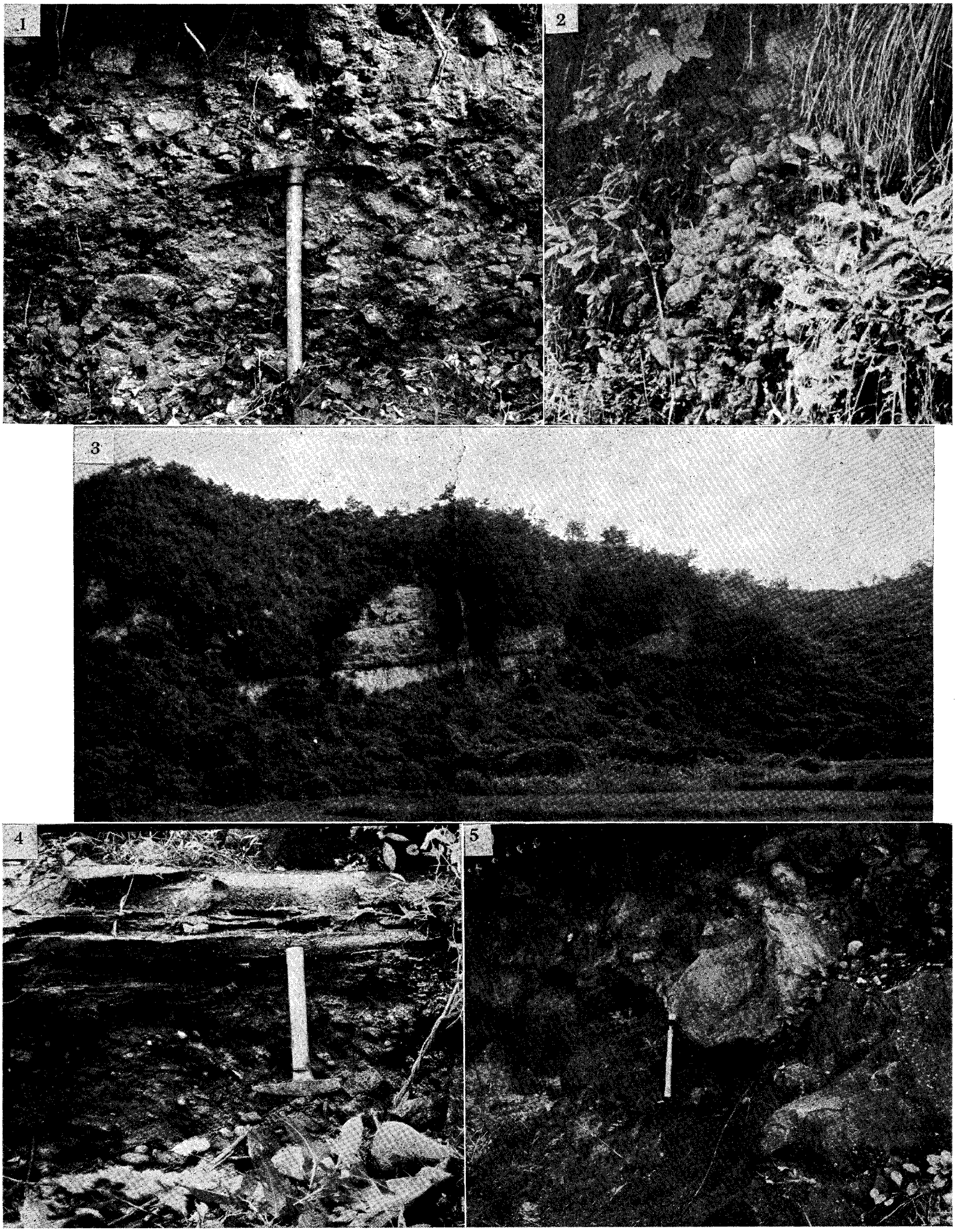
Fig. 3. Outcrop showing the unconformity between the Shirasaka and Goyasu formations. The Goyasu Formation covers the Shirasaka Formation with basal conglomerate. Locality; Bessho, Joban.

Fig. 4. Outcrop showing the unconformity between the Kunugidaira and Goyasu formations. The fragments derived from the lignite bed of the Kunugidaira Formation are included in the Goyasu Formation. Locality; Kami-Yamada, Yamada-cho.

Fig. 5. Outcrop showing the unconformity between the Iwaki and Goyasu formations. Here the basal conglomerate of the Goyasu Formation consists of rhyolitic rocks. Locality; West of Amakida, Yamada-cho.



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Explanation of Plate 30

Fig. 1. Close view of the basal conglomerate (granules of rhyolitic rocks predominate) Goyasu Formation. Locality; Hiragoronai, Yamada-cho.

Fig. 2. Outcrop of the basal conglomerate of the Nakayama Formation. Locality; West of Kami-Kamado, Watanabe-cho.

Fig. 3. Outcrop showing the unconformity between the Honya Mudstone Member of the Taira Formation and the Nakayama Formation. Locality; West of Kami-Kamado, Watanabe-cho.

Fig. 4. Outcrop of the basal conglomerate of the Izumi Group. Locality; Obayashi, Yamada-cho.

Fig. 5. Outcrop showing the unconformity between the Mizunoya and Nakayama formations. The basal conglomerate of the Nakayama Formation consists largely of andesitic or basaltic rocks. Locality; Miyamaguchi, Tono-cho.

Explanation of Plate 31

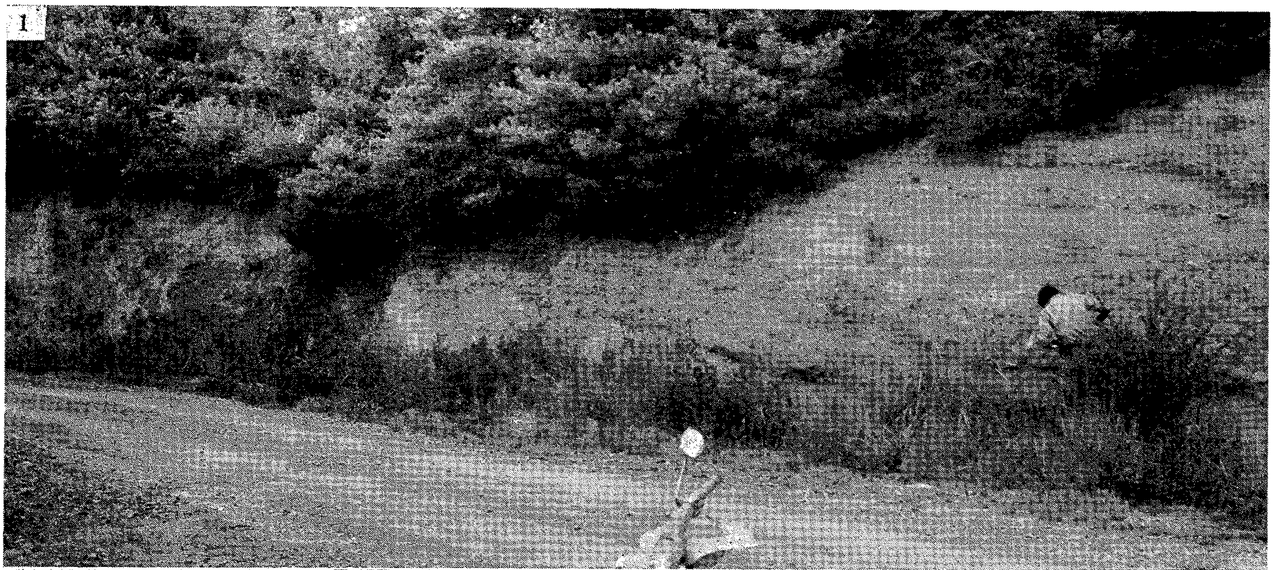
Fig. 1. Outcrop showing the unconformity between the granitic rock and the Iwaki Formation. The Iwaki Formation covers the granitic rock with basal conglomerate. Locality; The foot of Yunotake, Joban.

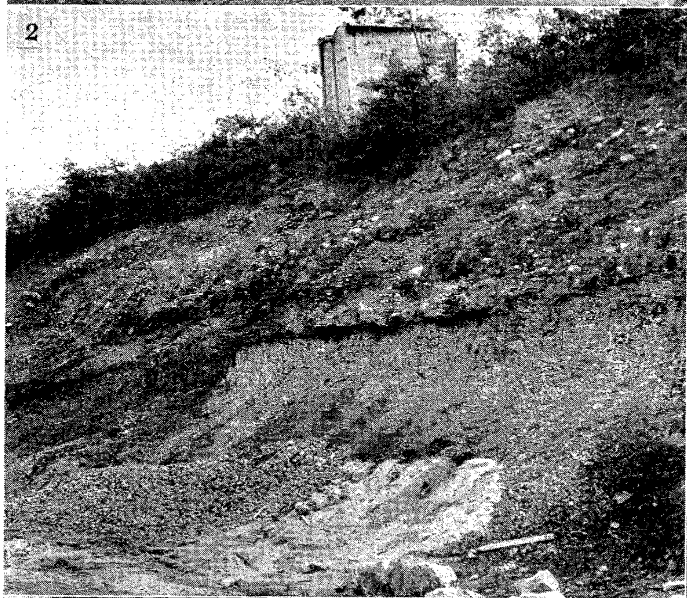
Fig. 2. Outcrop showing the unconformity between the Shirasaka and Kunugidaira formations. The Kunugidaira Formation lies on the Shirasaka Formation with basal conglomerate. Locality; East of Futatsushima, Kita-Ibaraki City.

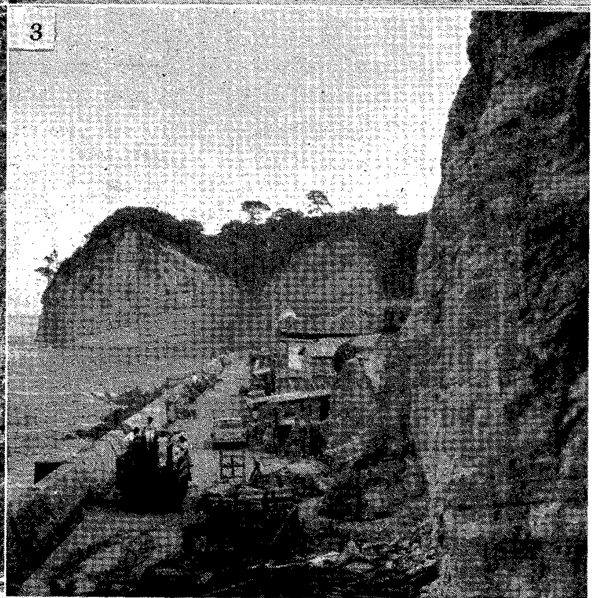
Fig. 3. Outcrop showing the unconformity between the Izumi Group and the Kameno-o Formation. The Izumi Group lies on the Kameno-o Formation with basal conglomerate. Locality; South of Hirakata Harbor, Kita-Ibaraki City.

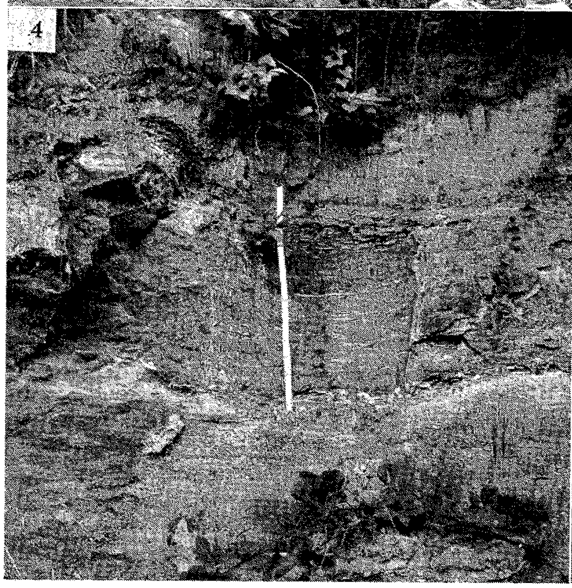
Fig. 4. Outcrop of the conglomerate-bearing coarse grained sandstone of the basal part of the Kami-Kamado Formation. Locality; Zukindaira, Izumi-cho.

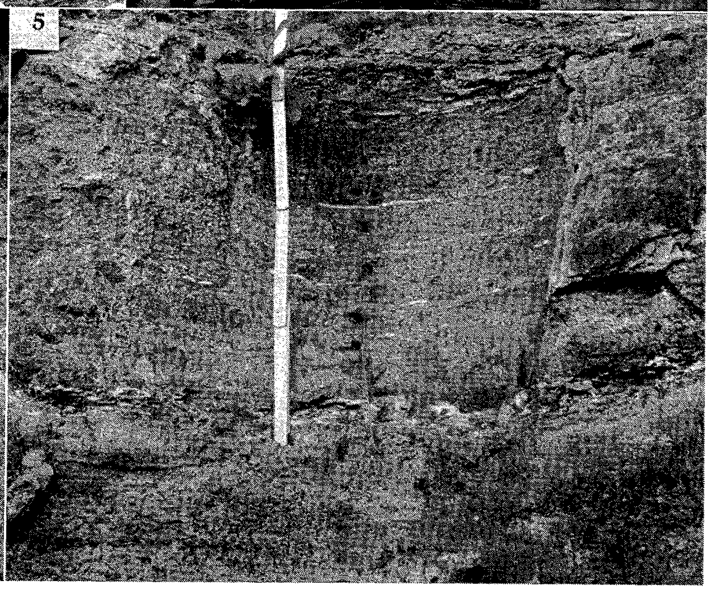
Fig. 5. Close view of Fig. 4.

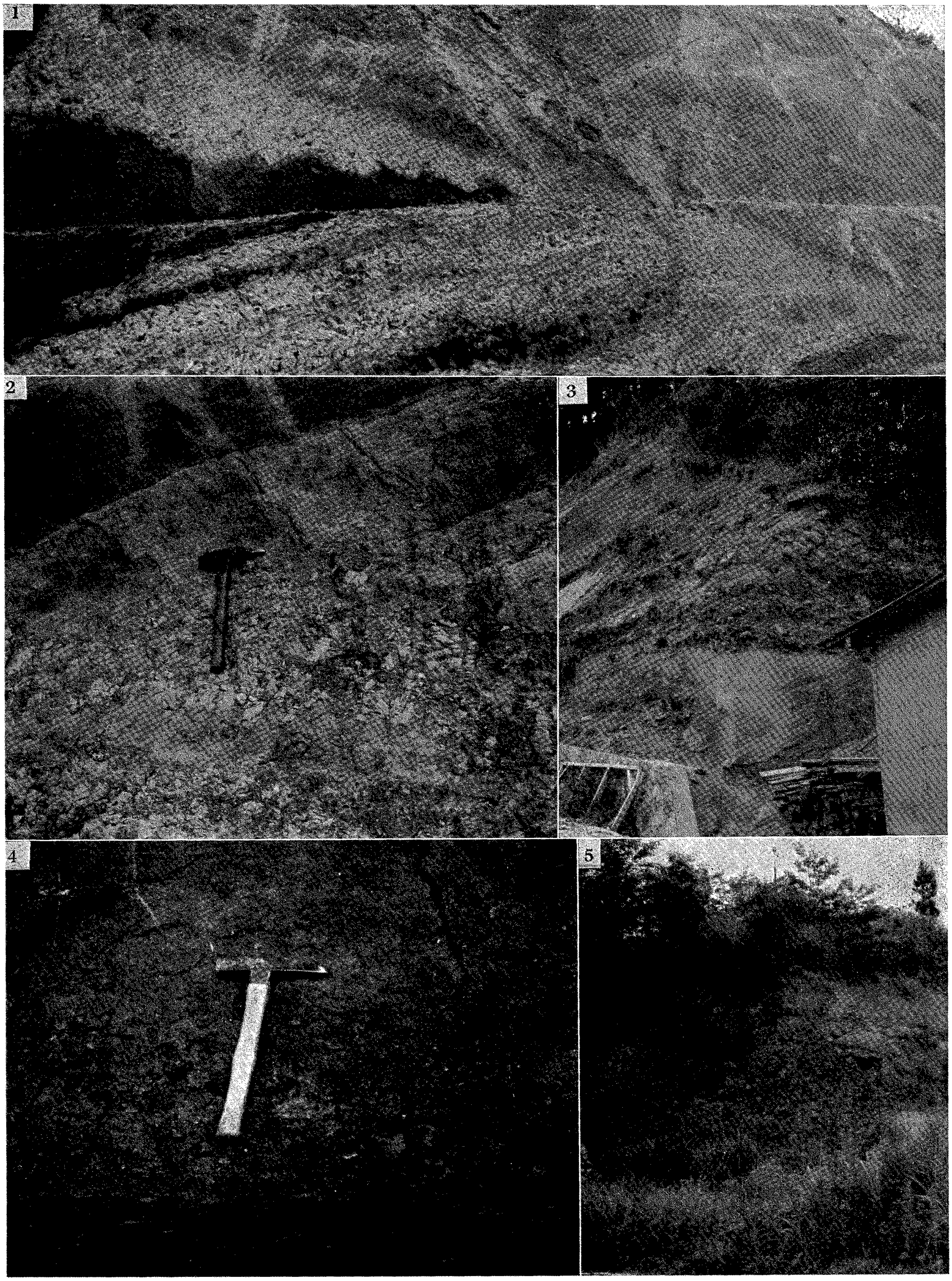








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Explanation of Plate 32

Fig. 1. Outcrop showing the unconformity between the Kameno-o Formation and the Izumi Group in a road-cut leading from Hirakata Harbor to Izura, Kita-Ibaraki City.

Fig. 2. Close view of Fig. 1. This basal conglomerate consists of shale of the Kameno-o Formation and mudstone of the Izumi Group.

Fig. 3. Outcrop of the basal part of the Sodetamayama Formation. Locality; East of Ueda, Ueda-cho.

Fig. 4. Outcrop showing the unconformity between the Mizunoya and Nakayama formations. Locality; Miyamaguchi, Tono-cho.

Fig. 5. Outcrop of the basal part of the Sodetamayama Formation. Locality; East of Ueda, Ueda-cho.

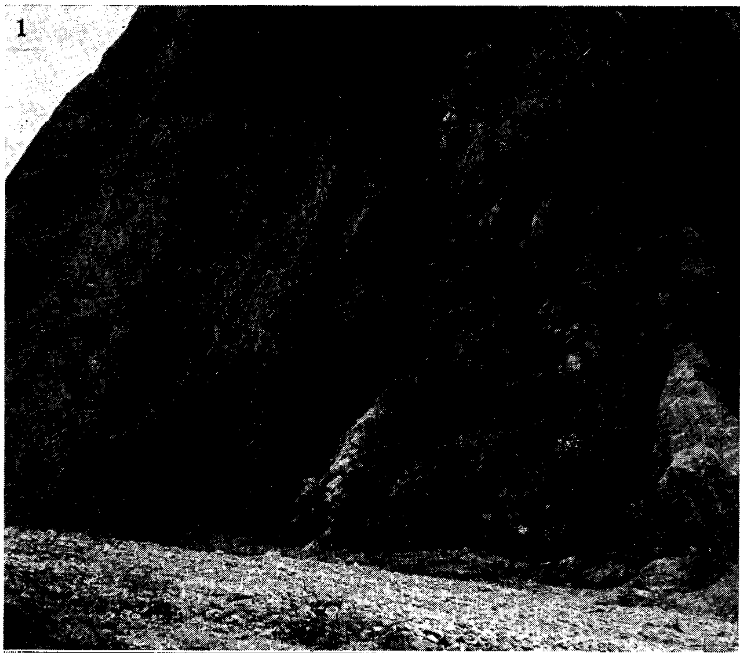
Explanation of Plate 33

Fig. 1. Outcrop of the Futaba flexure belt between the Goyasu and Sekinoue formations. Locality; West of Tsukiji, Hirono-cho.

Fig. 2. Outcrop of the Futaba thrust fault north of Asamigawa. At this locality the Goyasu Formation overlaps the Sekinoue Formation.

Figs. 3, 4. Close view of Fig. 2. In fig. 4 the minor fault with NW-SE trend cuts the minor fault with NNW-SSE direction, parallel to the Futaba thrust fault.

Fig. 5. Outcrop of the minor fault in the Nakayama Formation. Locality; The entrance to Kawakami Village.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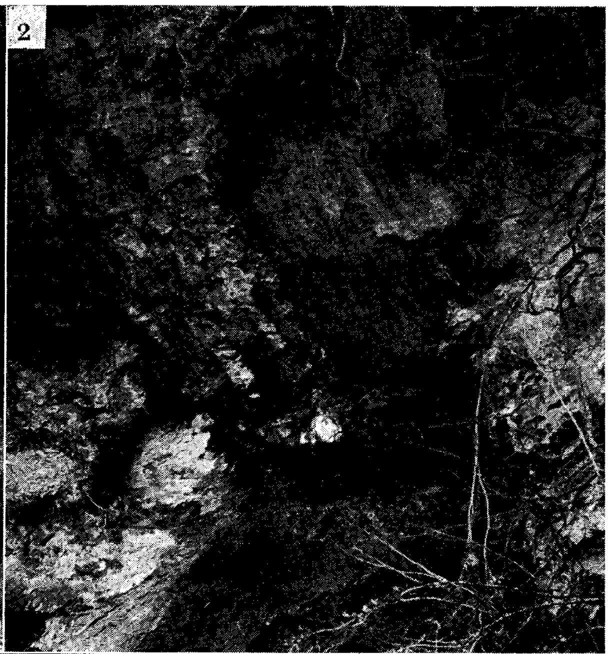
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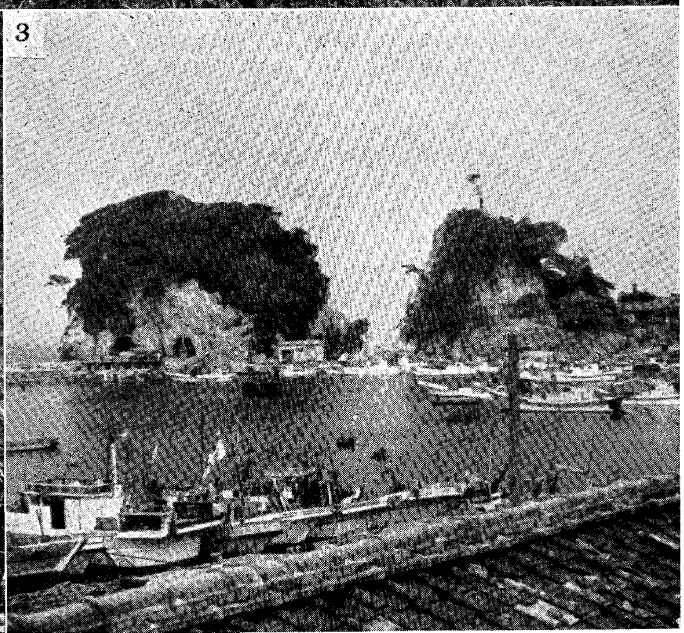
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Explanation of Plate 34

Fig. 1. Outcrop of the Shirasaka fault. Locality; Matsukusune, Taira. The strike and dip of this fault plane are N60°W and 70°S. This fault is between the upper part of the Goyasu (left side) Formation and the Misawa Sandstone Member of the Taira Formation (right side).

Fig. 2. Outcrop of the Akai fault. This occurs between the granitic rock and the Iwaki Formation. Locality; South of Joju, Ogawa-cho.

Fig. 3. Outcrop of the Hirakata fault. This occurs between the Izumi Group (left side island) and the Kameno-o Formation (right side island). Locality; Hirakata Harbor, Kita-Ibaraki City.

Fig. 4. Minor fault between the basal conglomerate of the Goyasu Formation and mudstone of the Kunugidaira Formation. Locality; Taki, Tono-cho.

Explanation of Plate 35

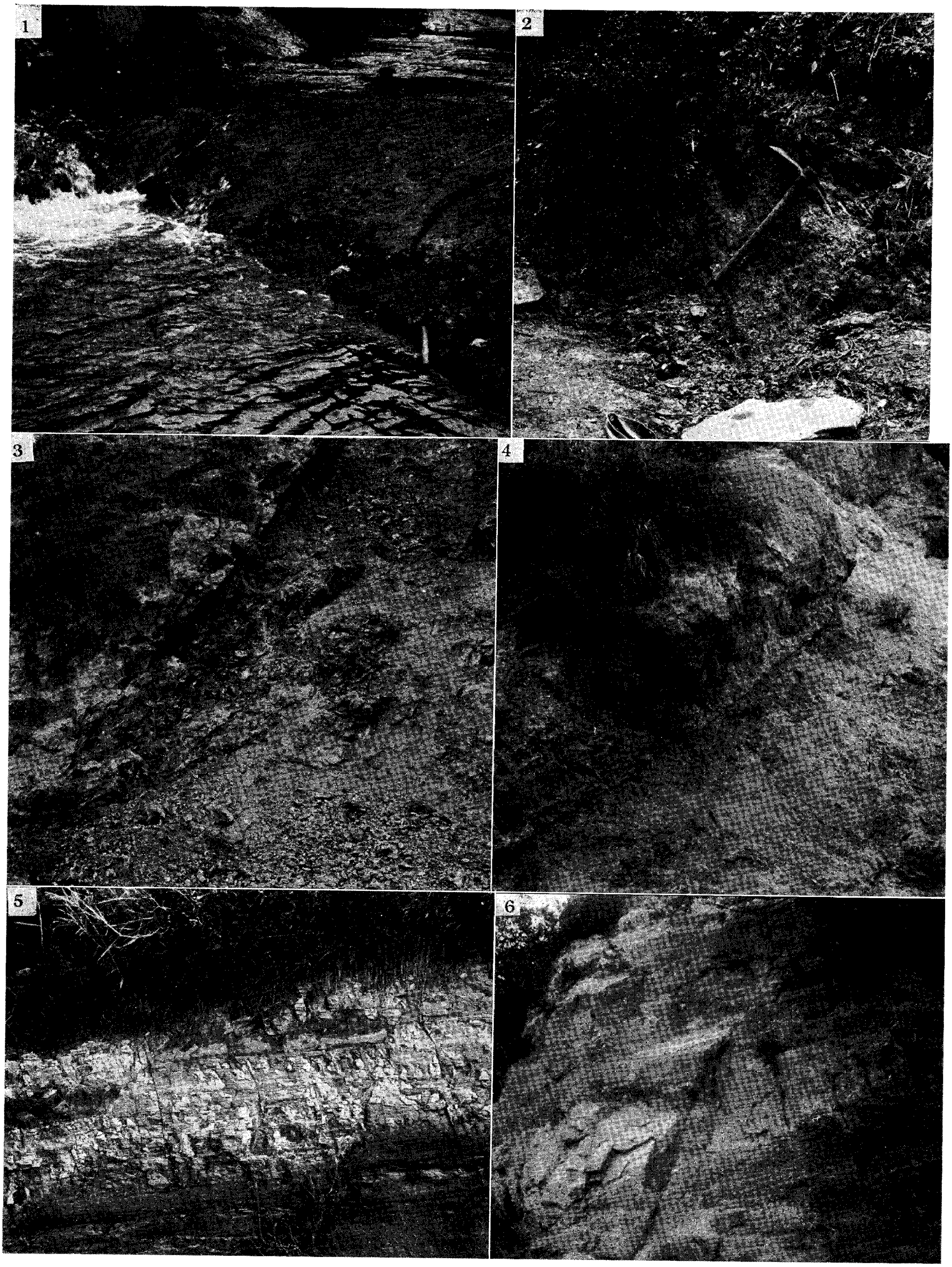
Fig. 1. Outcrop of the minor fault between the Kameno-o and Nakayama formations. Locality; Kadono, Tono-cho.

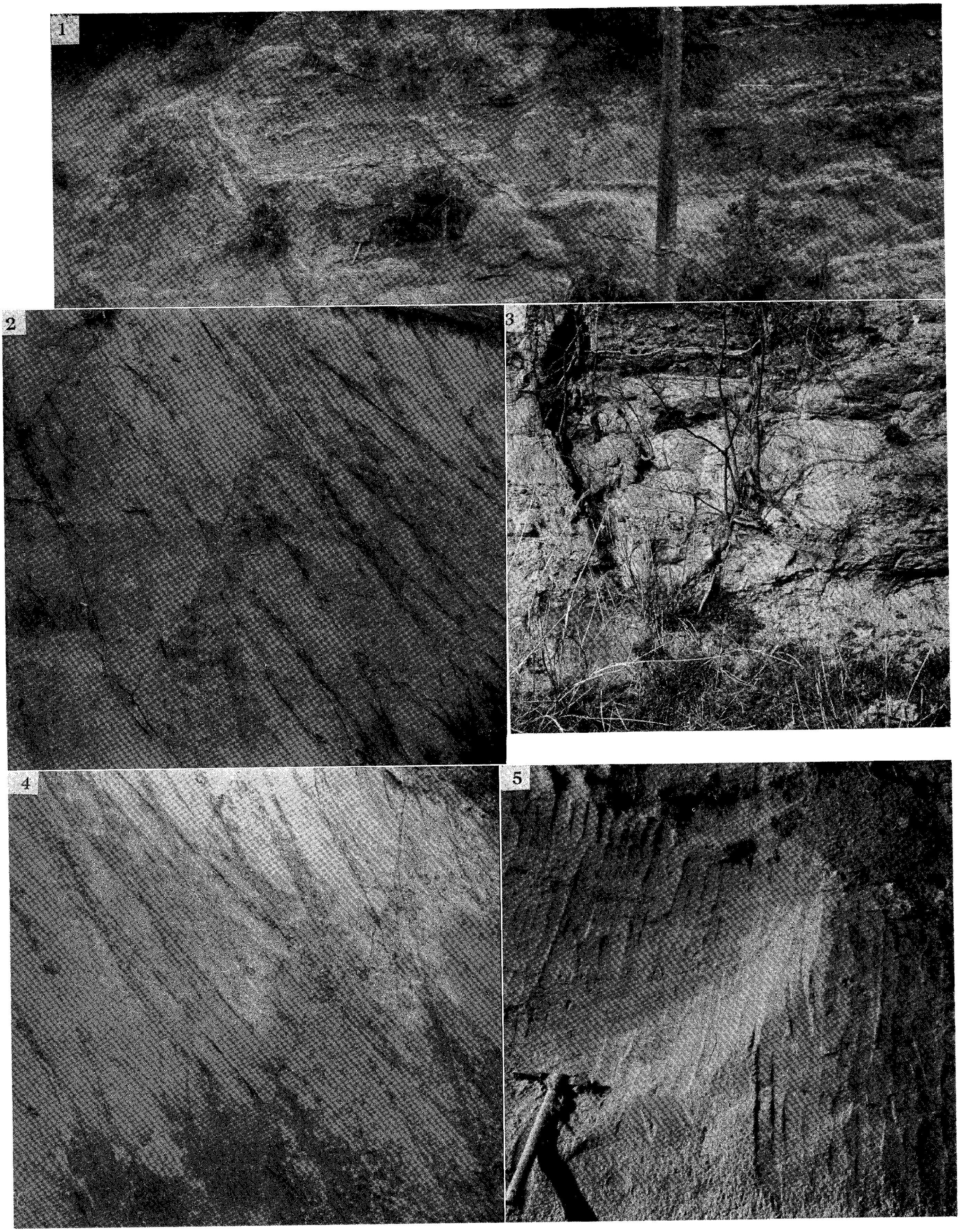
Fig. 2. Outcrop of a minor fault between the amphibolite and the Kunugidaira Formation. Locality; Taki, Tono-cho.

Figs. 3, 4. Outcrop of a minor fault between the Honya Mudstone Member and the Misawa Sandstone Member, both of the Taira Formation. Locality; Fig. 3 is at Ena, Fig. 4 is at Oshiro, both in Kashima-cho.

Fig. 5. Outcrop of a minor fault in the Kameno-o Formation. Locality; Ebata, Yamada-cho.

Fig. 6. Outcrop of a minor fault in the Misawa Sandstone Member of the Taira Formation. Locality; Ena, Ena-cho.





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Explanation of Plate 36

Fig. 1. Conjugate set of minor faults in the Iwaki Formation. Locality; Tamachi, Ogawa-cho (T-35).

Fig. 2. Conjugate set of shear joints in the Mizunoya Formation. Locality; Yunagaya, Joban (T-19).

Fig. 3. Conjugate set of minor faults in the Iwaki Formation. Locality; Kita-Yoshima, Yoshima-cho (I-3).

Fig. 4. Conjugate set of shear joints in the Mizunoya Formation. Locality; Mizunoya, Joban.

Fig. 5. Conjugate set of shear joints in the Goyasu Formation. Locality; North of Kita-Asamigawa (H-3).

Explanation of Plate 37

Surface shearing developed in a tri-axial test series.
Sample: Shaly mudstone of the Shirasaka Formation

Fig. 1. at atmospheric pressure
Fig. 2. at 300 bars confining pressure
Fig. 3. at 500 bars confining pressure
Fig. 4. at 800 bars confining pressure

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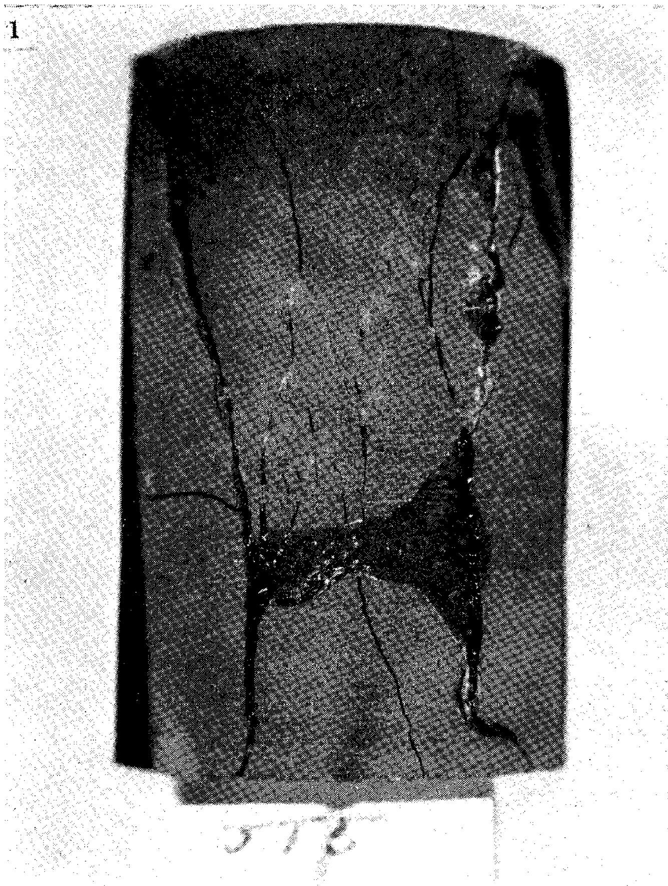

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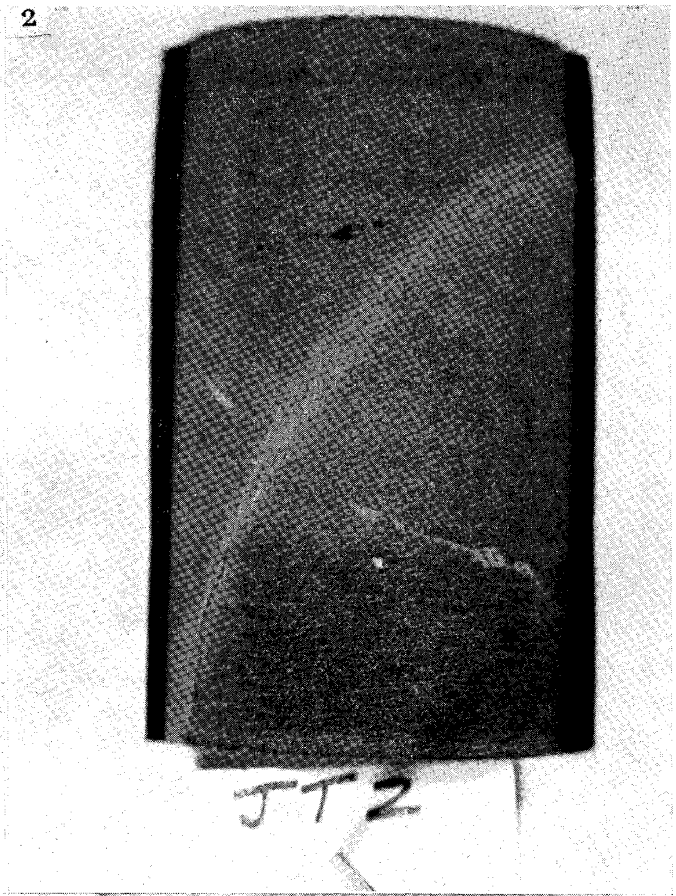

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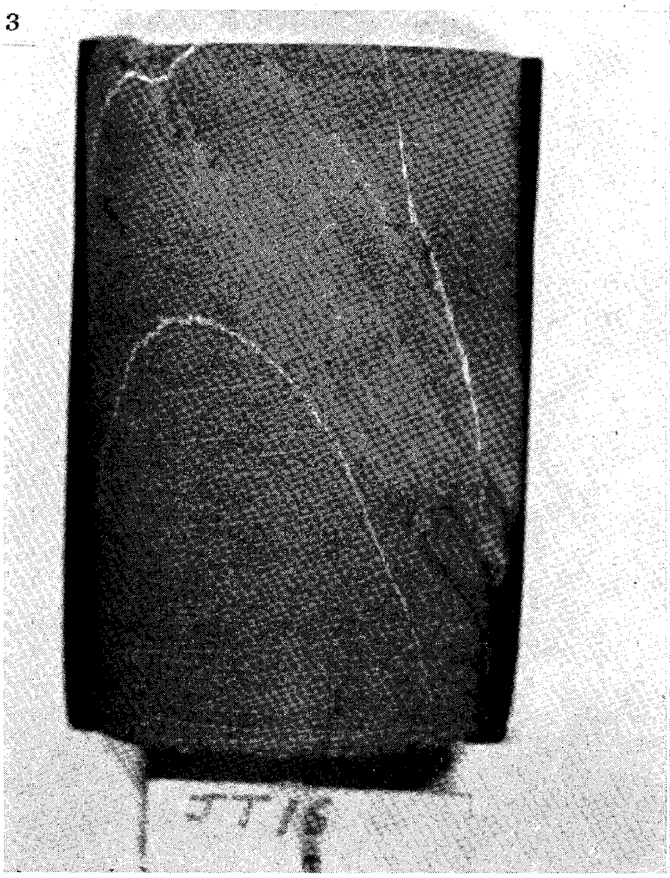

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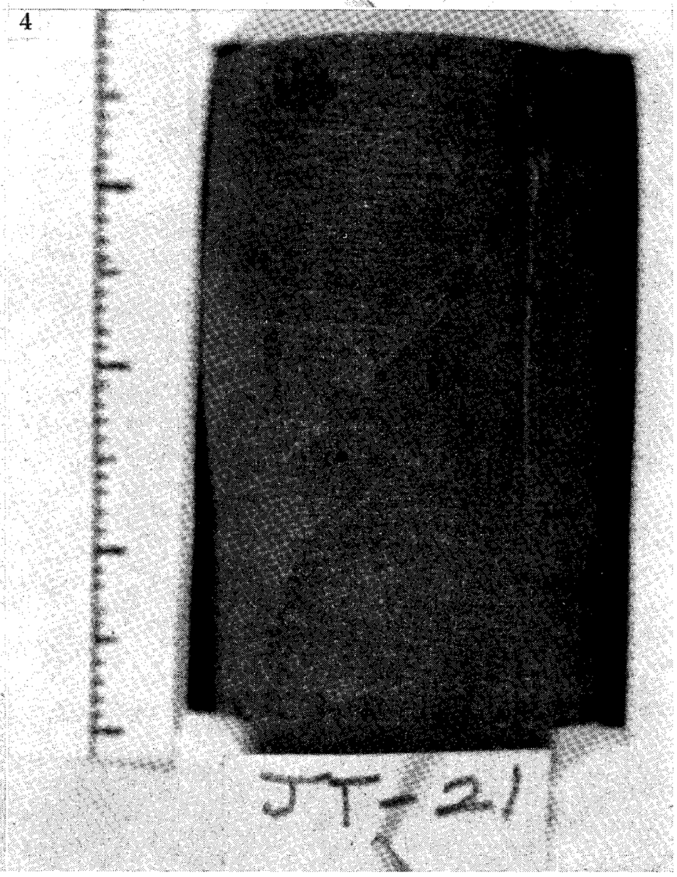

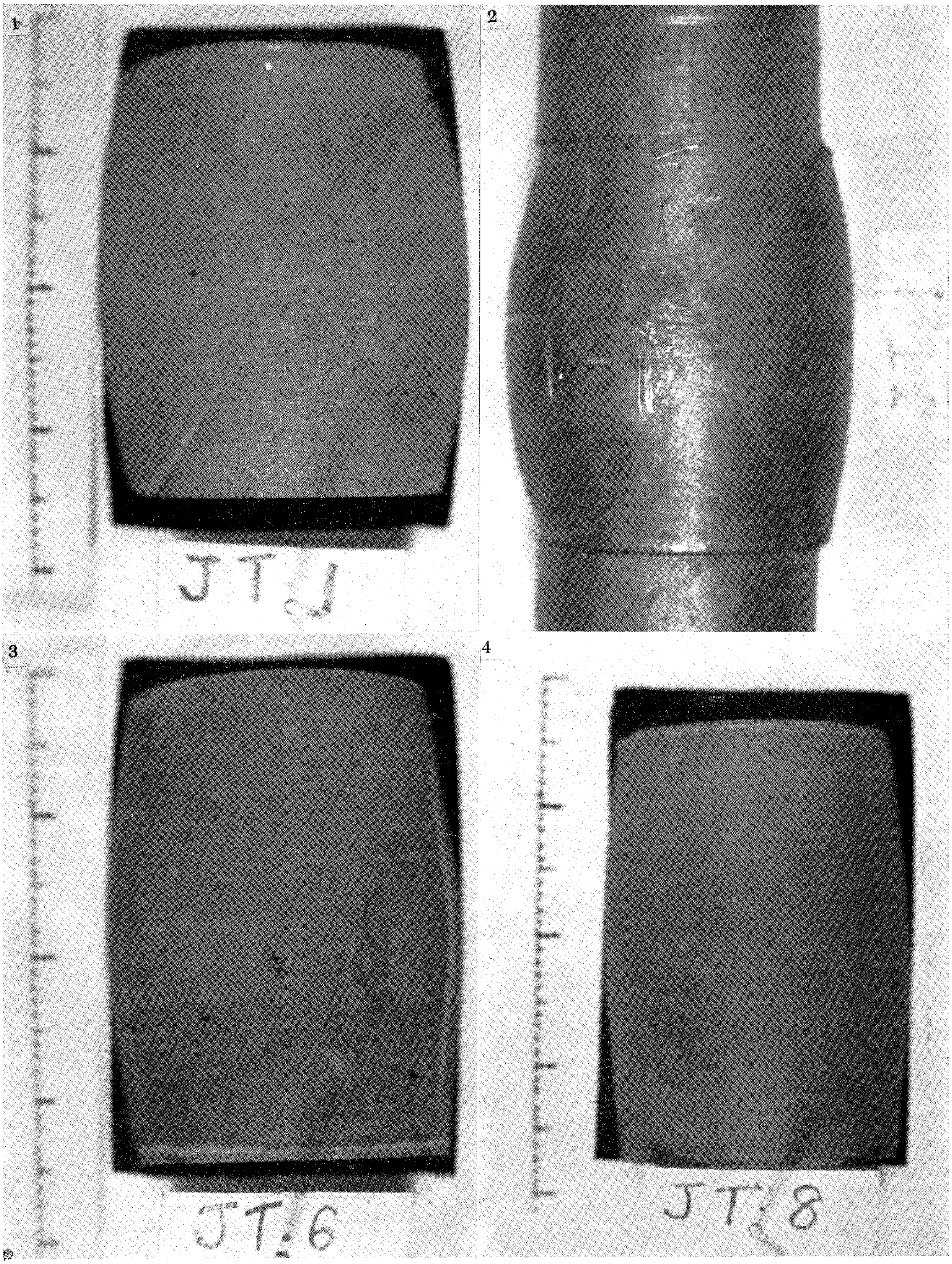
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Explanation of Plate 38

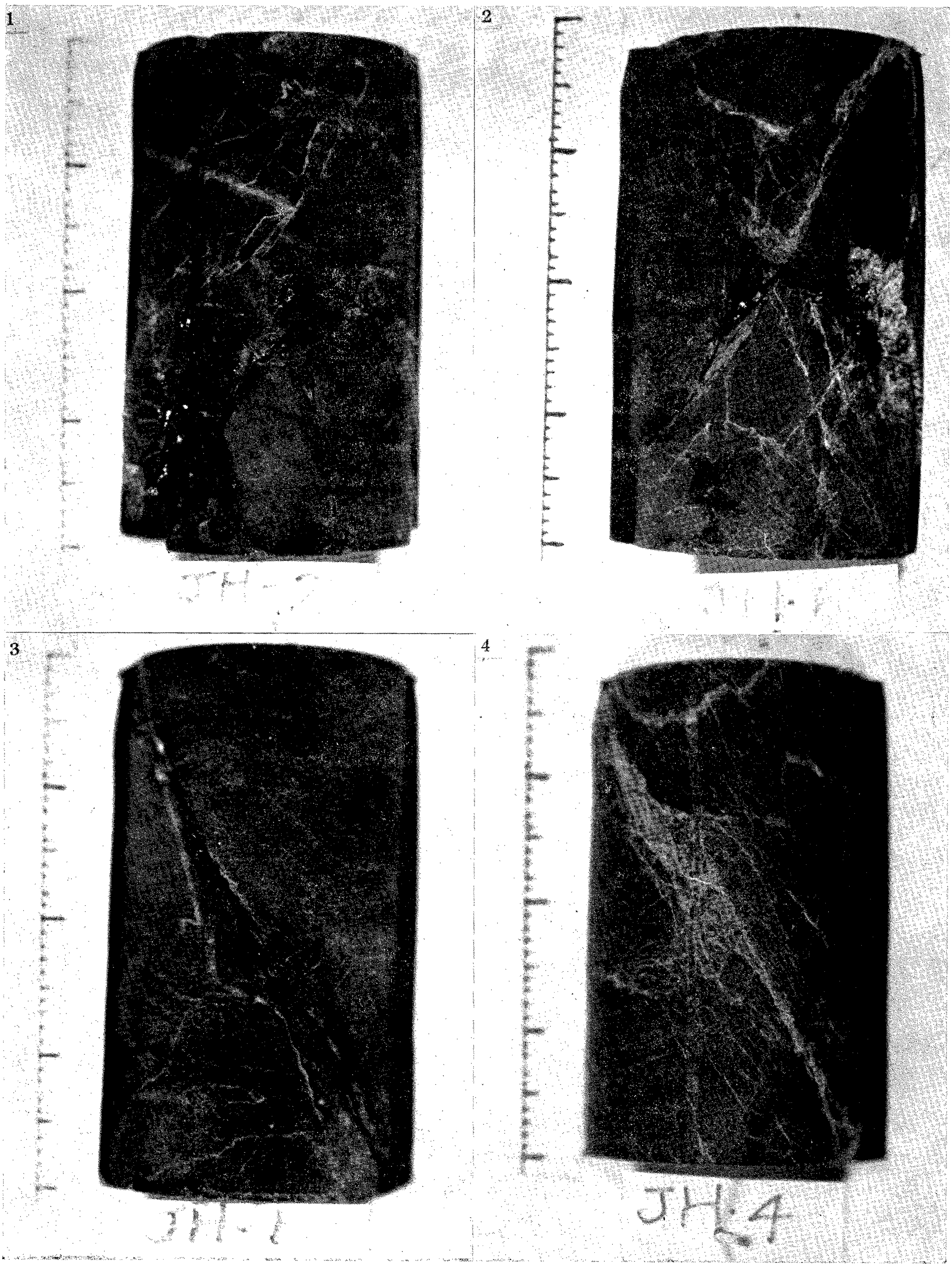
Surface shearing developed in a tri-axial test series.
Sample: Shaly mudstone of the Shirasaka Formation

Fig. 1. at 1,000 bars confining pressure
Fig. 2. at 1,000 bars confining pressure (covered by a jacket)
Fig. 3. at 1,500 bars confining pressure

Explanation of Plate 39

Surface shearing developed in a tri-axial test series.
Sample: Amphibolite of the basement rocks.

Fig. 1. failure at atmospheric pressure
Fig. 2. failure at 500 bars confining pressure
Fig. 3. failure at 1,000 bars confining pressure
Fig. 4. failure at 1,500 bars confining pressure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